Quarkonia Theory

What do we know?

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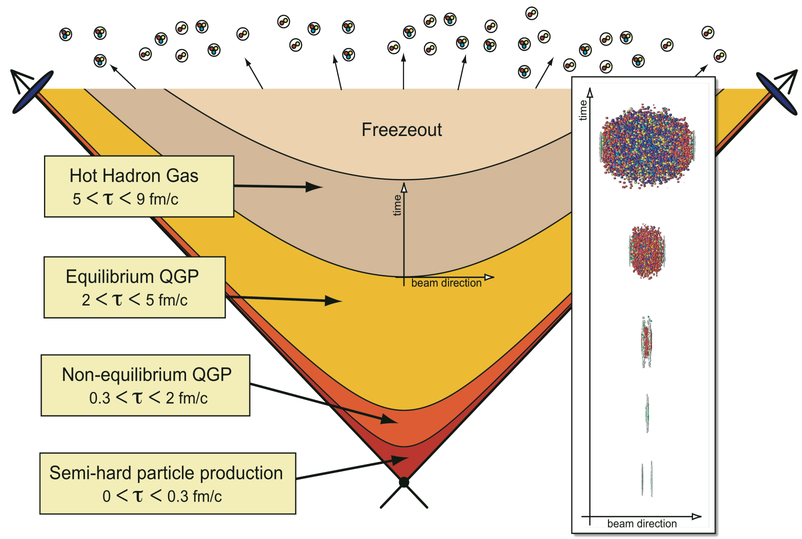
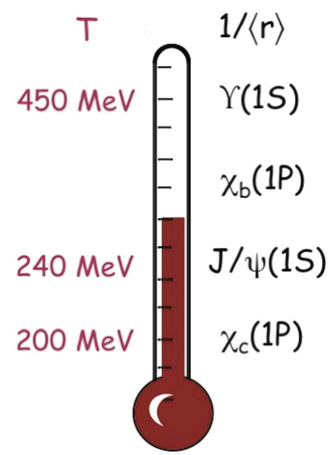
KENT STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY

Our main character: quarkonia

- Ground state charmonium and bottomonium have vacuum binding energies on the order of 0.5 – 1 GeV, implying formation times that are less than ~ 0.5 fm/c
- They are rare probes
- Quarkonia masses are higher than the QGP temperature; therefore, thermal production is strongly suppressed
- From a theoretical perspective, one can make use of heavy quark effective theory to approach the problem systematically both (vacuum and finite T)



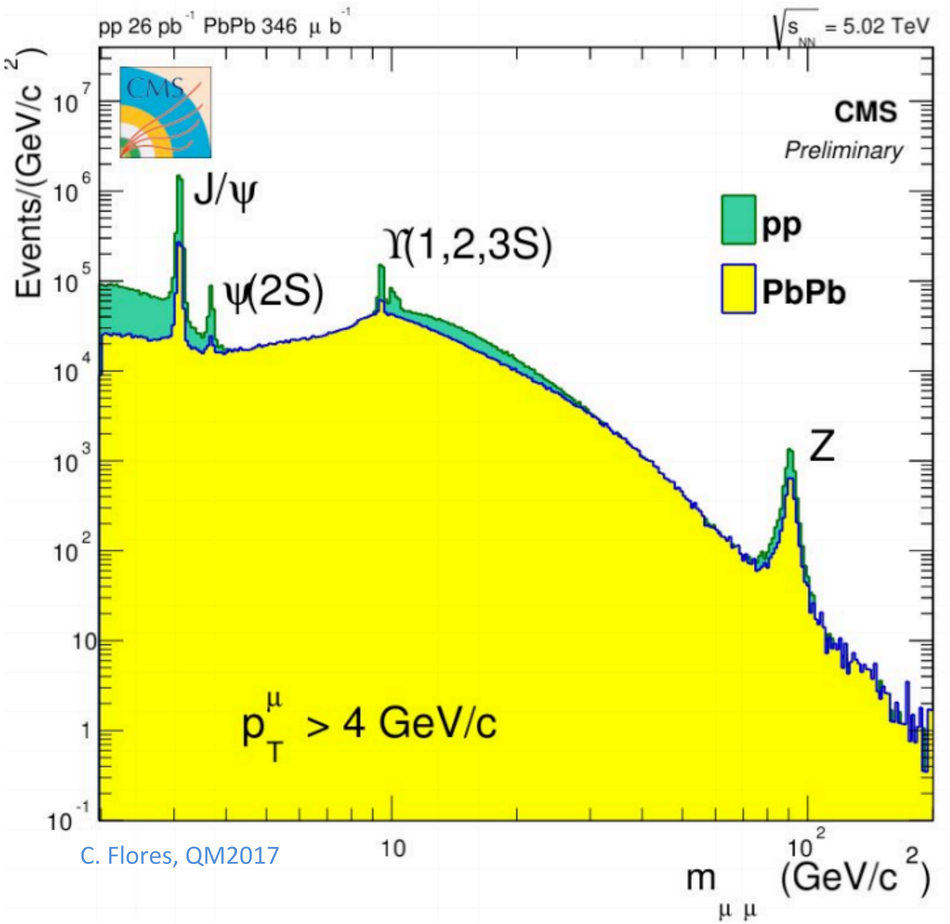


A. Mocsy, P. Petreczky, and MS, 1302.2180

This cartoon is too simple! There are <u>no discrete thresholds in T</u>. More on this later…

A generated medium?

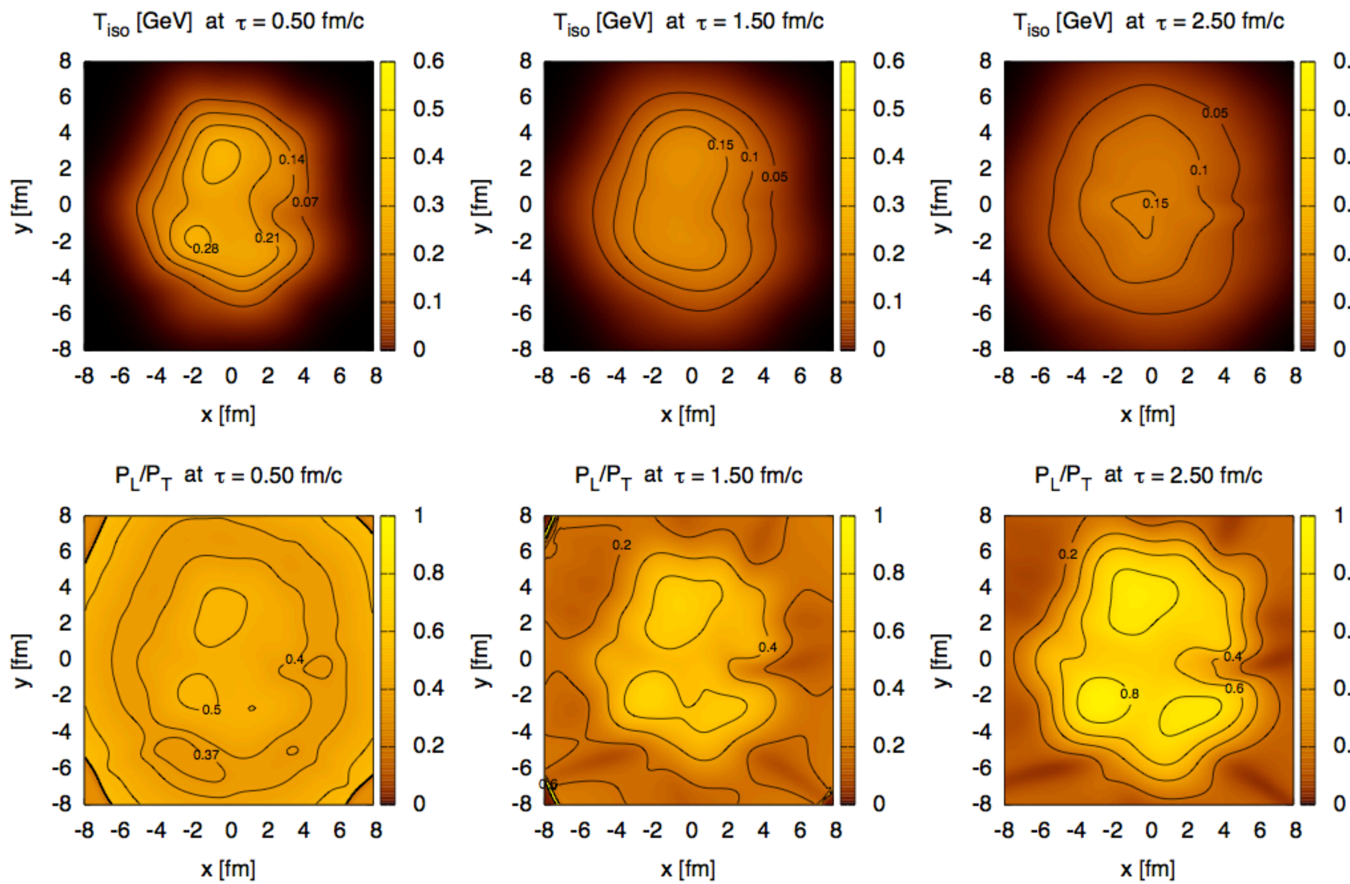
The **CMS** (Compact Muon Solenoid) experiment has measured dimuon spectra for both pp and Pb-Pb collisions.



C. Flores, QM2017

Survival probability

For in-medium suppression, given the population of quarkonia states at some τ_0, we can simply integrate the instantaneous decay of the state $\Gamma(\tau,x,y,\eta)$ over the QGP spatiotemporal evolution to obtain the **survival probability**.



Pb-Pb @ 2.76 TeV
T_0 = 600 MeV
τ_0 = 0.25 fm/c
b = 7 fm

M. Martinez, R. Ryblewski, MS, arXiv:1204.1473

Other pieces to the story

pp reference

Experimental measurements rely on R_{AA} which is **defined relative to the pp cross section**; therefore, we need reliable pp reference data and a firm theoretical understanding of open- and closed-charm production in pp collisions

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Cold nuclear matter effects

Quarkonia production is also affected by **nuclear-modified PDFs, Cronin effect, and co-movers** which can result in enhancement or suppression of quarkonia production depending on the kinematic window.

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Regeneration

If the population of open- and closed-charm states is high, then it is possible for quarkonia to be regenerated through **recombination of open heavy flavor with a liberated heavy flavor**. There can also be local recombination of an individual bound state due to medium interactions.

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Viscous QGP modeling

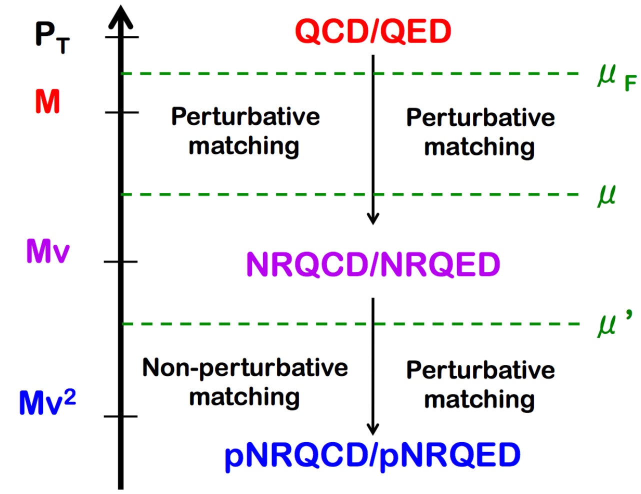
Quarkonia are sensitive to the full spatio-temporal evolution of the QGP. Need to compute dynamical processes including non-equilibrium corrections. **Should use codes that reproduce experimental data for bulk observables** such as particle spectra and azimuthal flow.

Quarkonia production in pp

Quarkonia in pp collisions

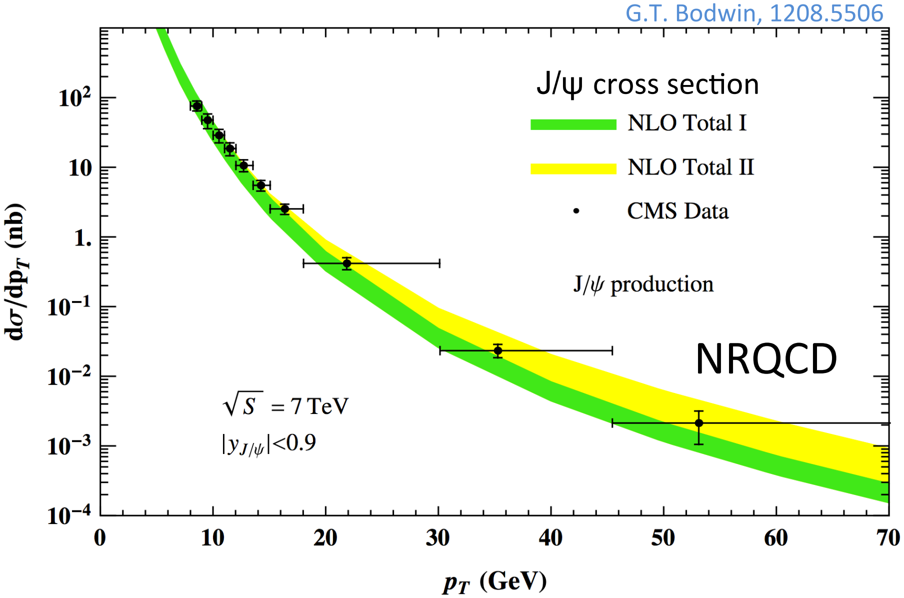
- Different theoretical approaches
  - **NRQCD factorization approach**
    Bodwin, Braaten, and Lepage
  - **Fragmentation approach**
    Kang, Qiu, and Sterman
  - **Color-singlet model (CSM)**
    Kartvelishvili, Likhoded, Slabospitsky, Chang, Baier, ...
  - **Color-evaporation model (CEM)**
    Fritzsch, Halzen, Amundson, Eboli, Gregores, Vogt, ...
  - **k_T - factorization approach**
    Yuan, Chao, Baranov, Zotov, and Szczurek

- NRQCD factorization approach is quite successful; in agreement with most of the inclusive production data (polarized production still a problem)



Figure, Jianwei Qiu

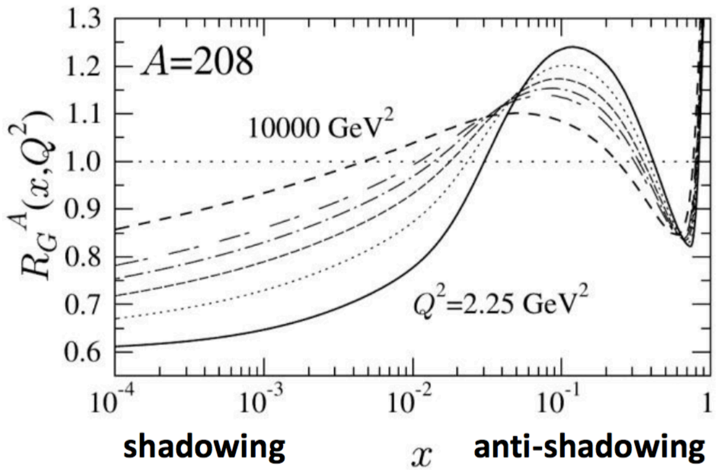
G.T. Bodwin, 1208.5506



Quarkonia production in pA

Cold nuclear matter effects

- **Can enhance or suppress quarkonium production**
  - **Nuclear PDFs:**
    - Shadowing: decreases production
    - Anti-shadowing: increases production
  - **Color Glass Condensate (CGC):** high gluon occupation numbers can affect production (includes some of the other effects listed)
  - **Cronin effect:** broadening of p_T spectra due to NN interactions in nucleus
  - **Nuclear absorption:** disassociation of a bound state passing through a nucleus
  - **Parton energy loss:** elastic scattering when moving through the nucleus before hard scattering
  - **Co-mover absorption:** hadrons propagating together with the bound state interact with it, e.g. J/psi + pi → D + D + X
- Cold nuclear matter effects present in pA and AA collisions; **less important for bottomonia**



Bjorken x for Υ(1S)

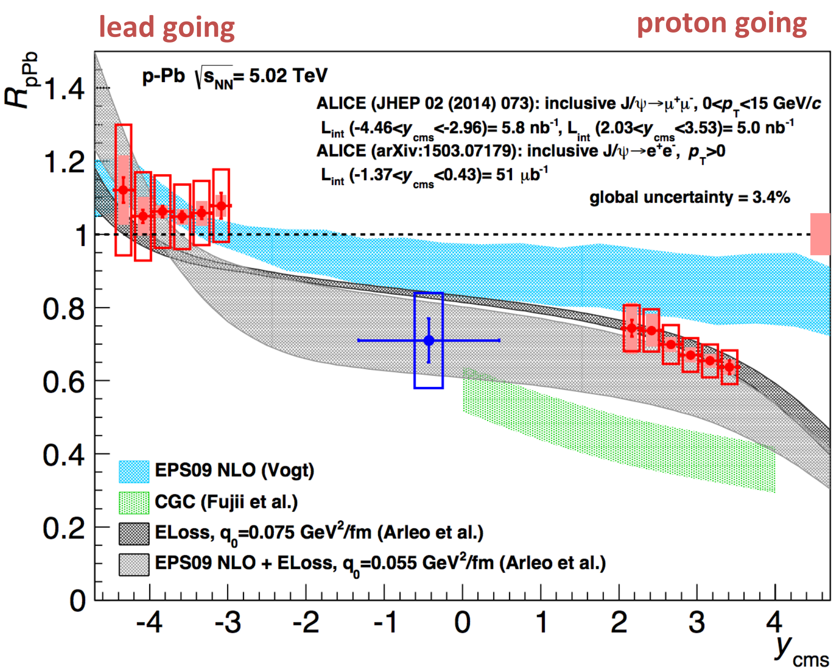
Ballpark estimate for $g + g \rightarrow \Upsilon(1s)$

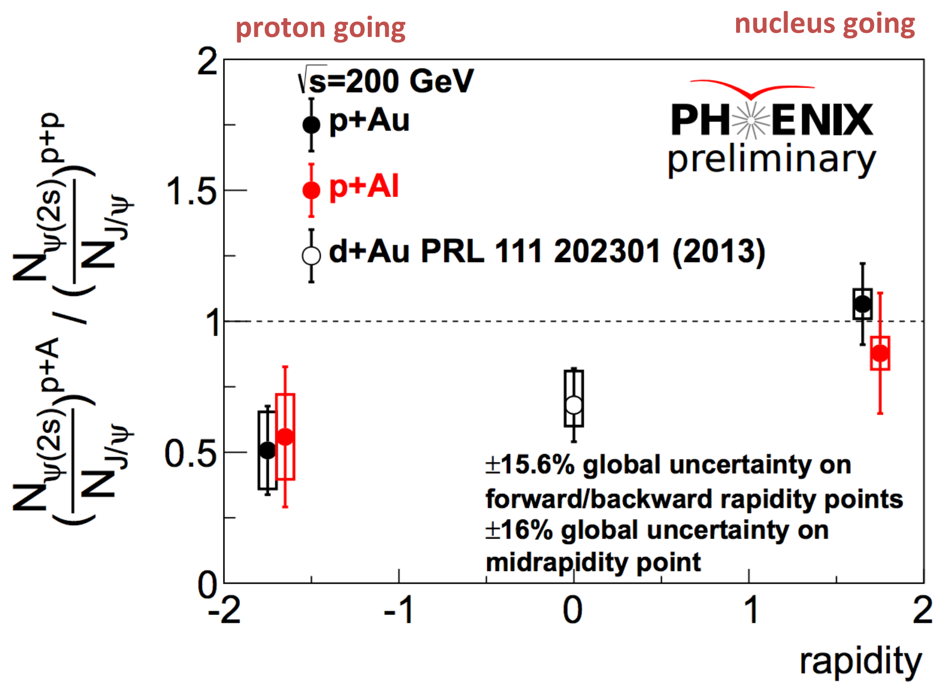
$$x_{1,2} = \frac{M}{\sqrt{s_{NN}}} e^{\pm y_{CM}}$$

p going
$5 \times 10^{-5} < x < 2 \times 10^{-4}$ → shadowing

Pb going
$4 \times 10^{-2} < x < 2 \times 10^{-1}$ → anti-shadowing

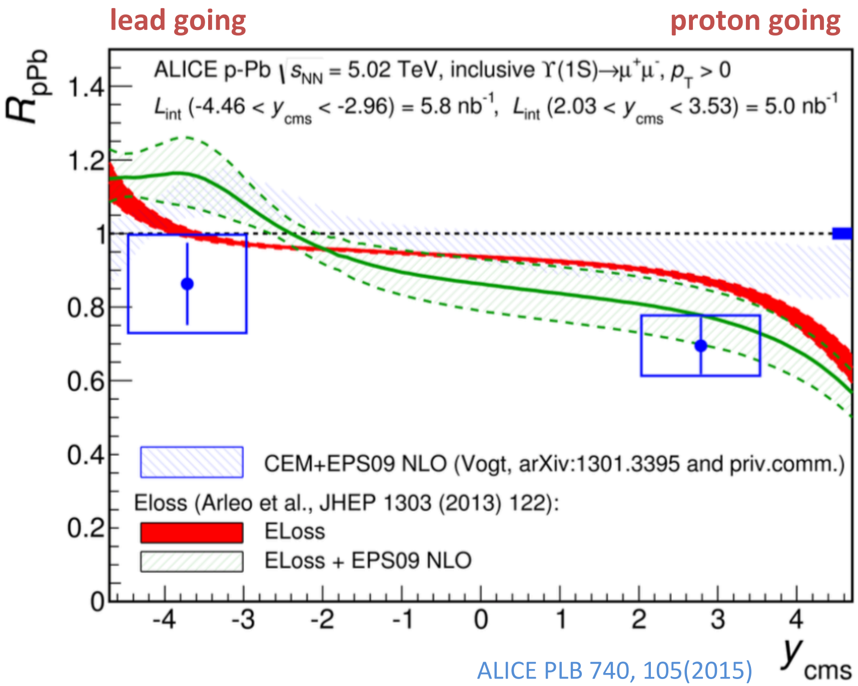
pA - Charmonia states



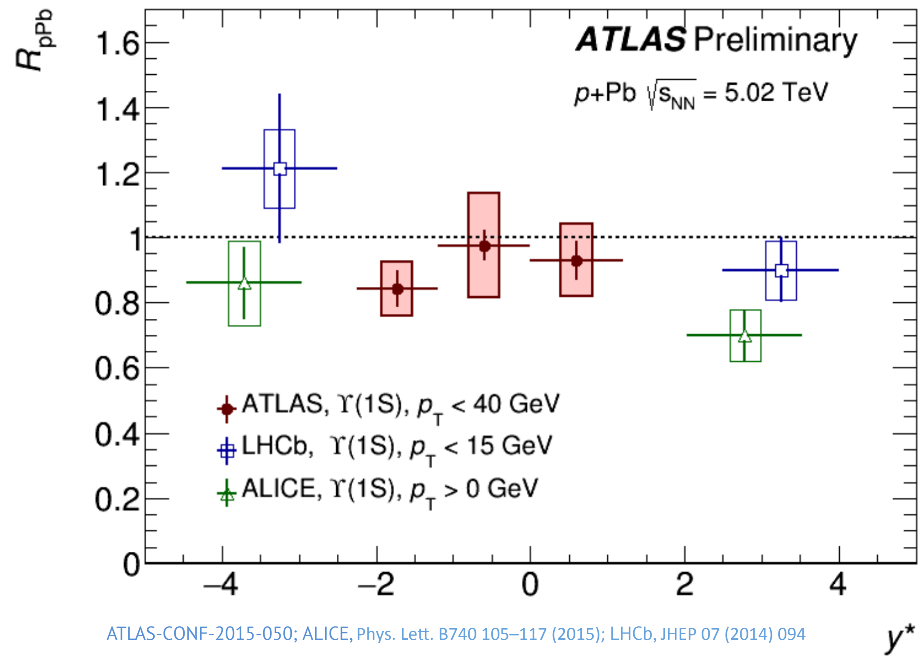


- Coherent energy loss and shadowing can explain the main characteristics of J/ψ production due to CNM.
- As a result, for charmonia, CNM effects must be taken into account in order to properly interpret the AA suppression data
- In most models shadowing and energy loss are expected to be almost identical
- However, this alone cannot describe the large ψ(2S) suppression; need enhanced suppression from **co-movers**?

pA - Bottomonia states



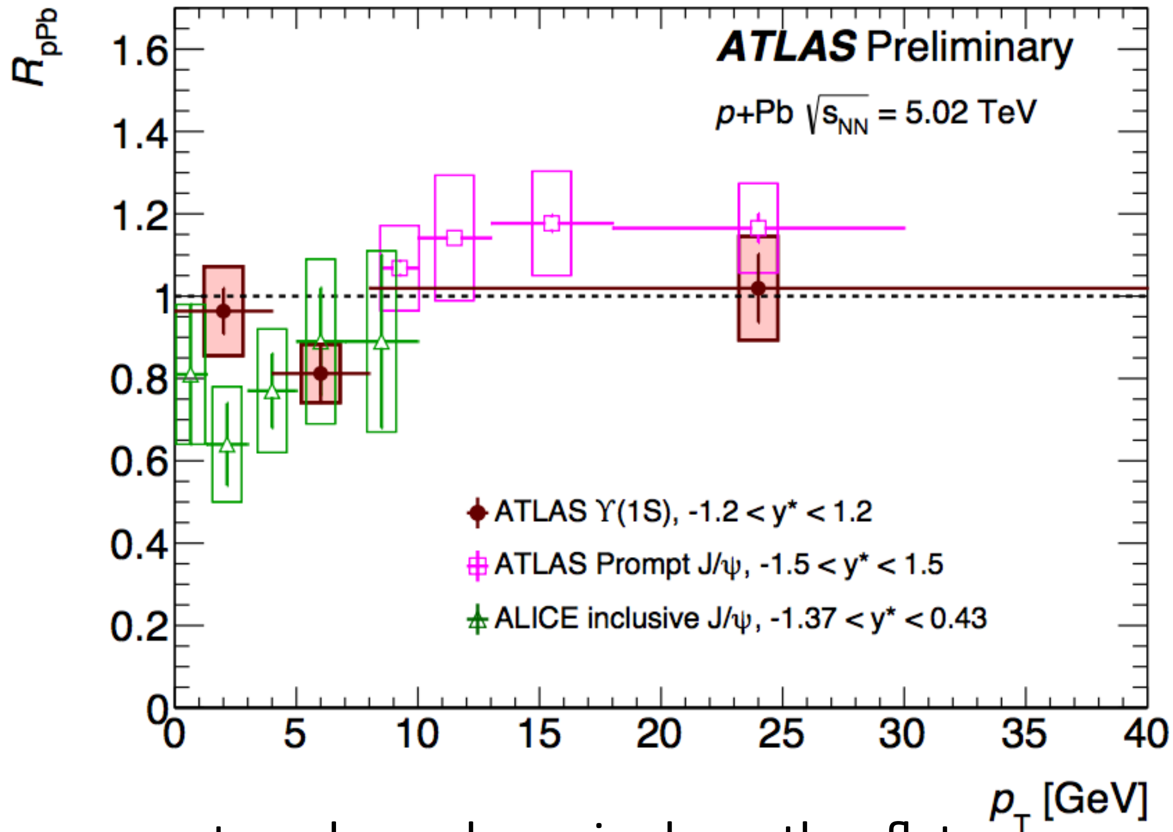
ALICE PLB 740, 105(2015)



ATLAS-CONF-2015-050; ALICE, Phys. Lett. B740 105–117 (2015); LHCb, JHEP 07 (2014) 094

- No significant rapidity dependence of (1s) R_{pPb}
- Suppression at forward rapidity and R_{pPb} is consistent with unity at backward rapidity
- Models predict maximal CNM effect ~ 10-20% at central rapidity

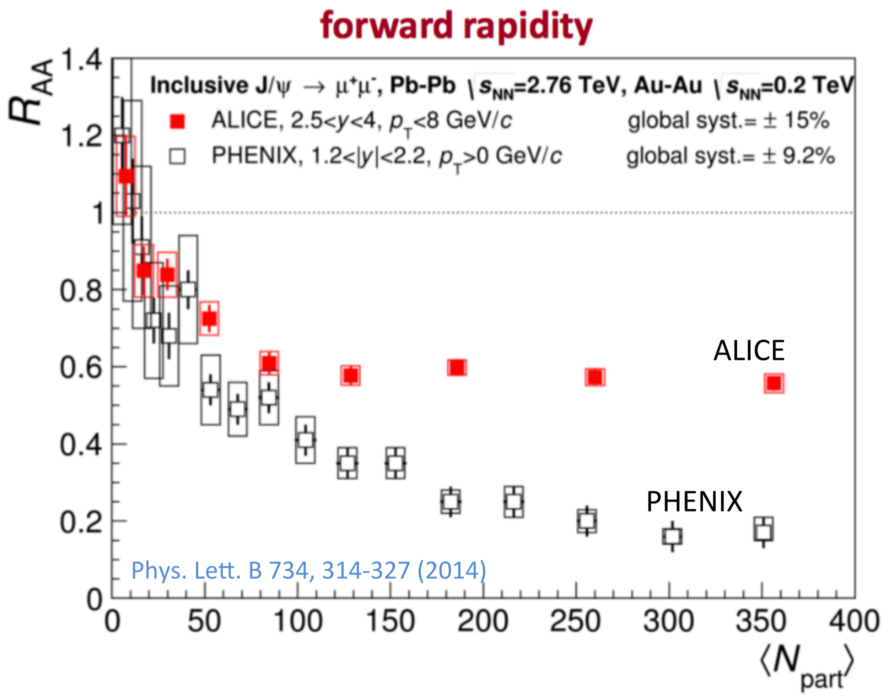
pA - Bottomonia states

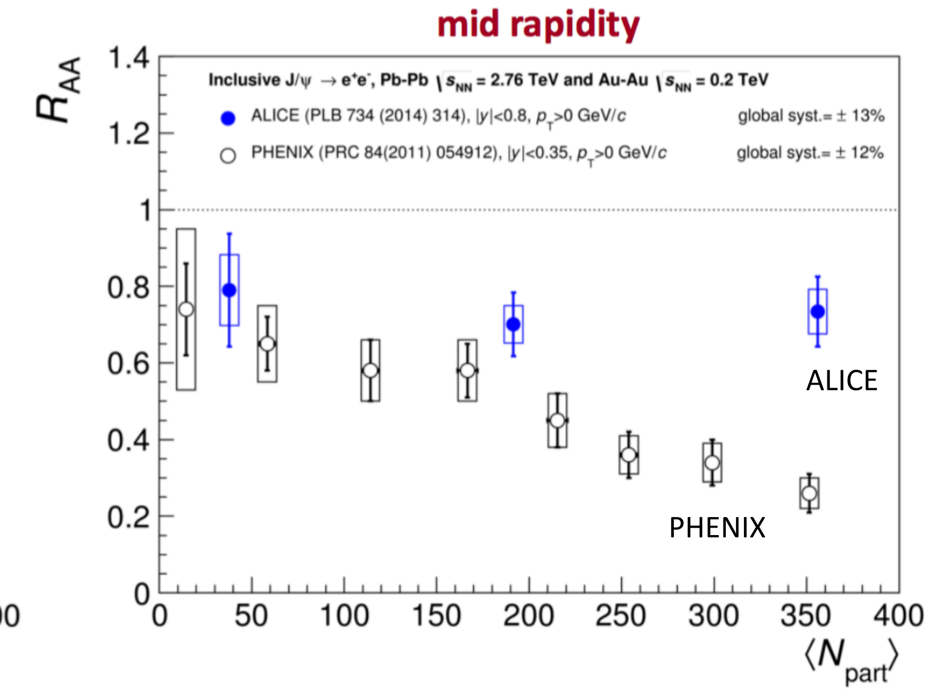


- Transverse momentum dependence is also rather flat
- Excited bottomonia measured by CMS show a stronger suppression with respect to the Y(1S), suggesting final state interactions or co-mover effect. Or is this perhaps a QGP droplet?

Quarkonia production in AA

AA – Charmonia states

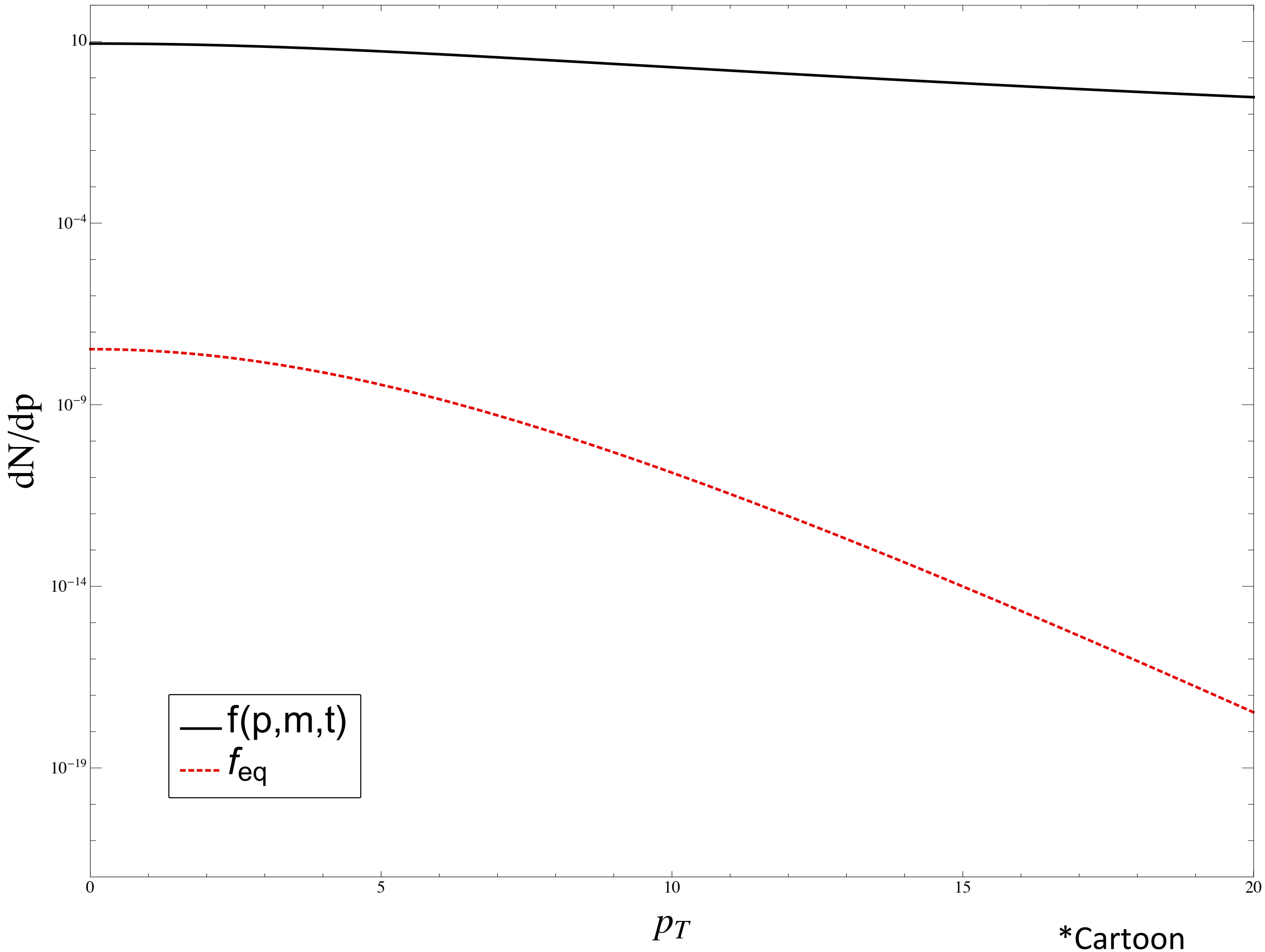




- No significant centrality dependence for ALICE $N_{part} > 70$
- Stronger J/ψ suppression at RHIC at both forward and mid rapidity!
- Evidence of regeneration of charmonia states?
- What about the p_T dependence?

AA – Charmonia states

- Based on the rate equation $\frac{\mathrm{d}N_{Y}(\tau)}{\mathrm{d}\tau} = -\Gamma_{Y}(T)\left[N_{Y}(\tau) - N_{Y}^{\mathrm{eq}}(T)\right]$



*Cartoon

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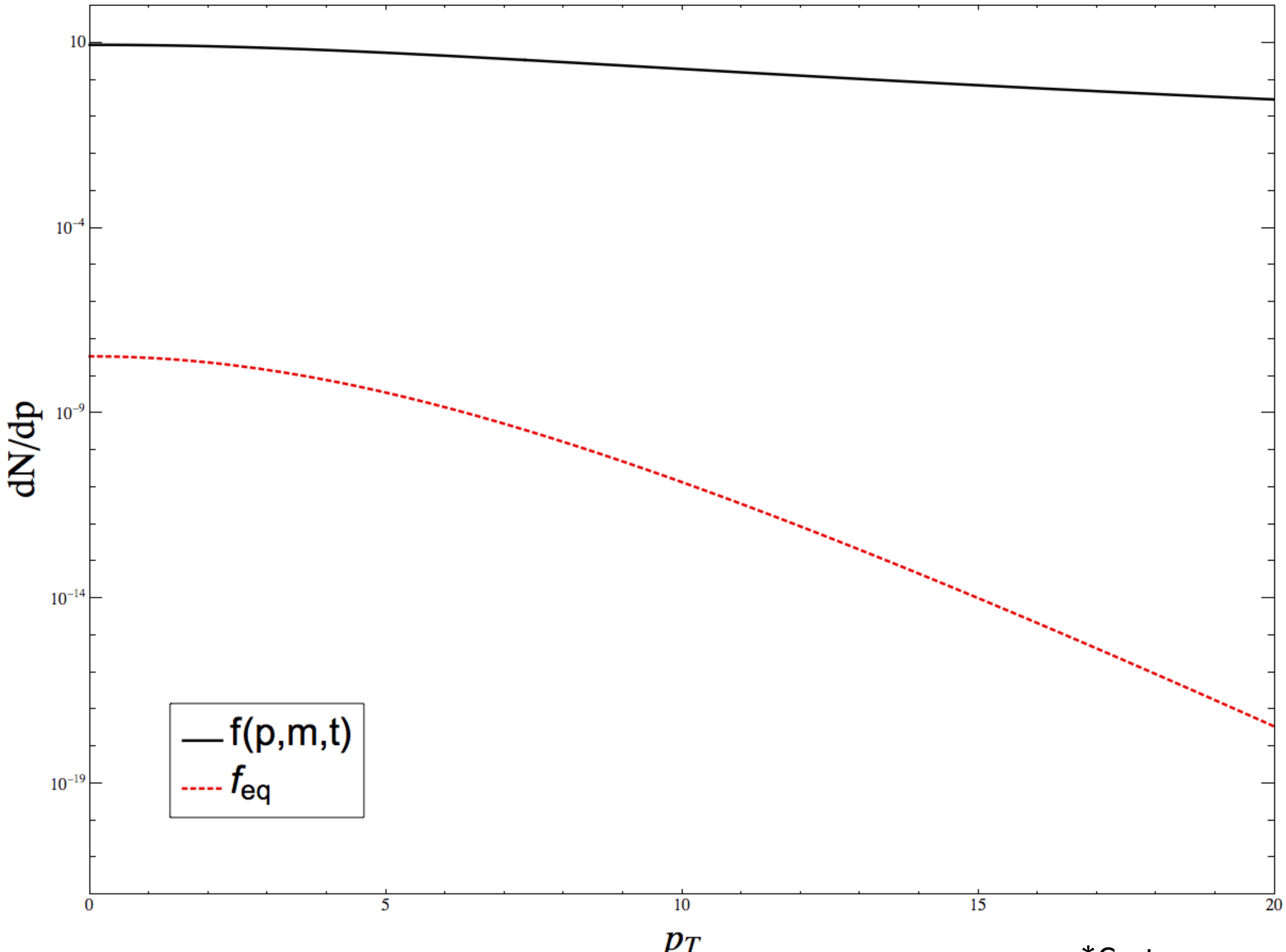

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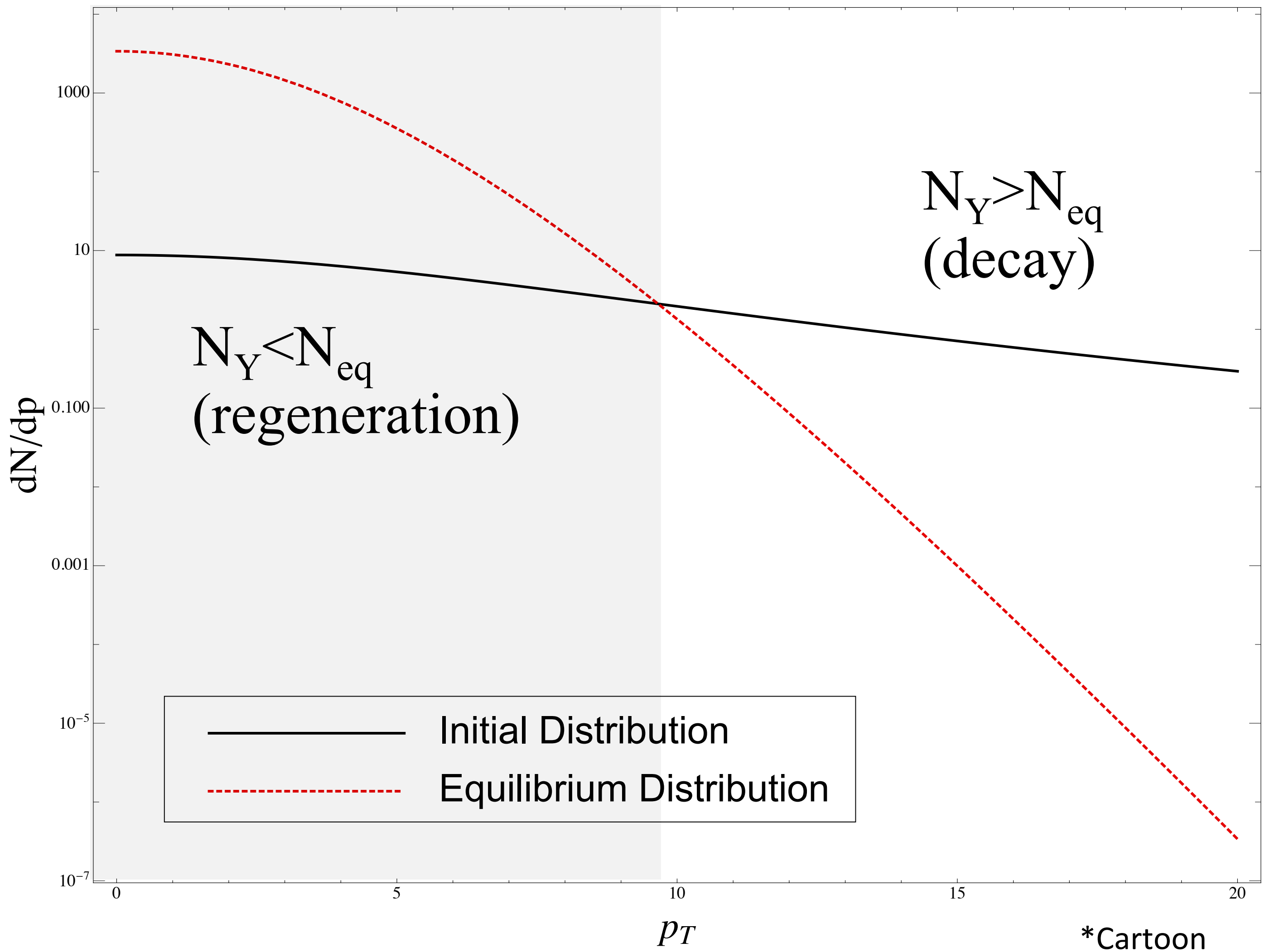
AA – Charmonia states

- Based on the rate equation $\frac{\mathrm{d}N_\Upsilon(\tau)}{\mathrm{d}\tau} = -\Gamma_\Upsilon(T)\left[N_\Upsilon(\tau) - N_\Upsilon^{\mathrm{eq}}(T)\right]$



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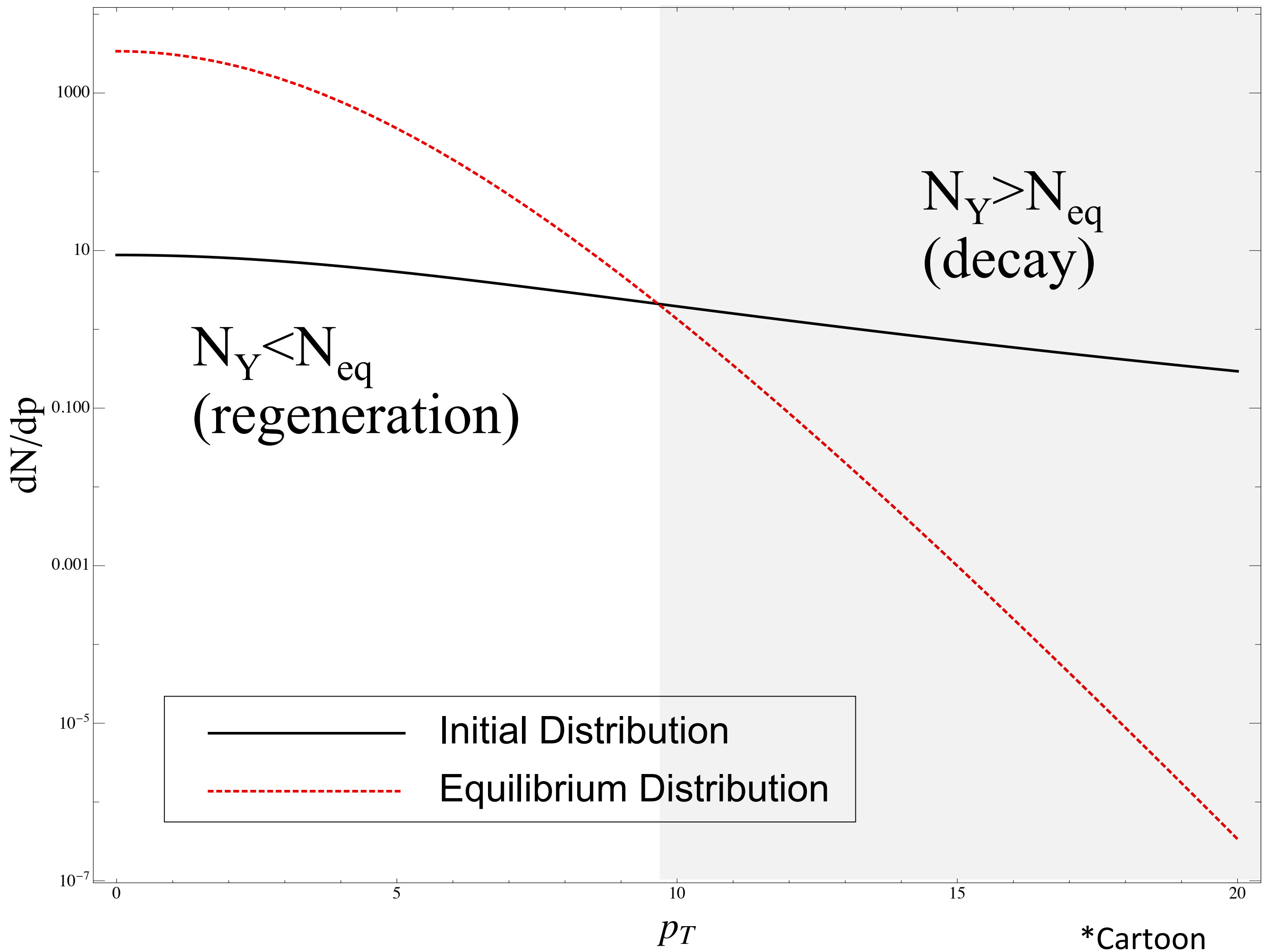

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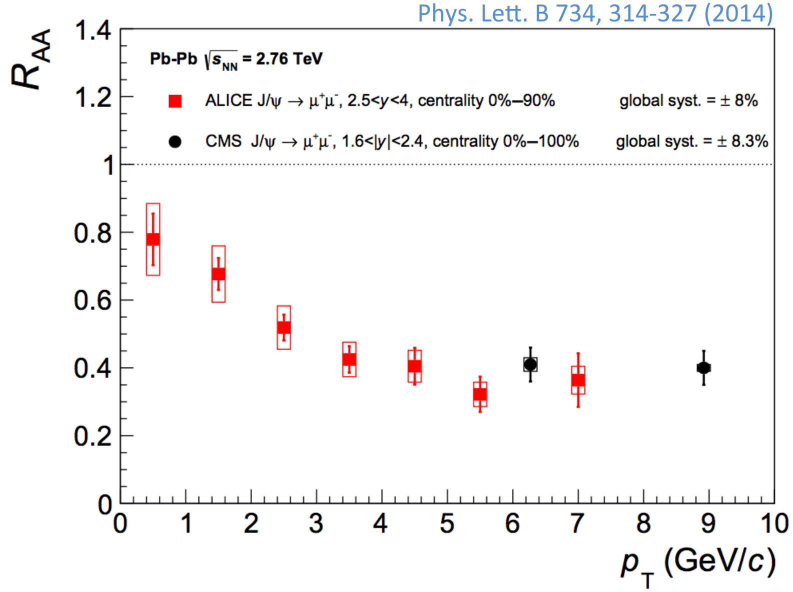
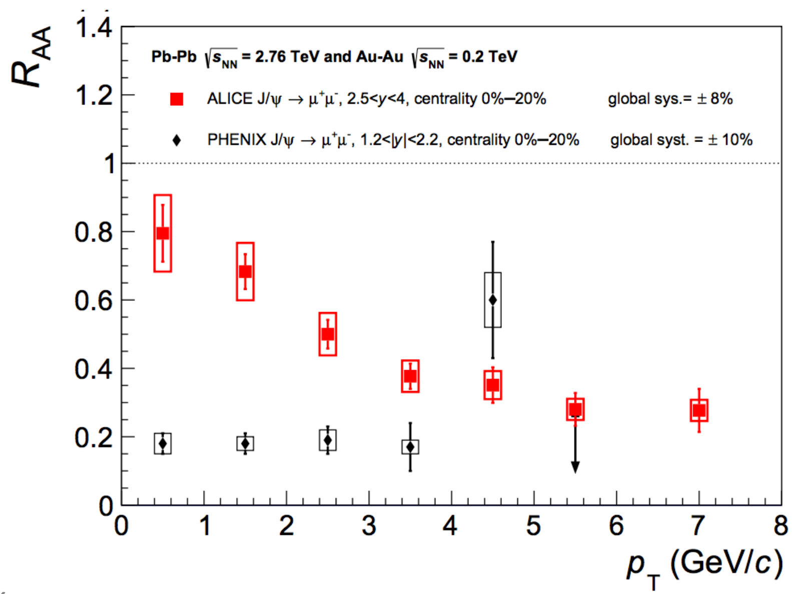
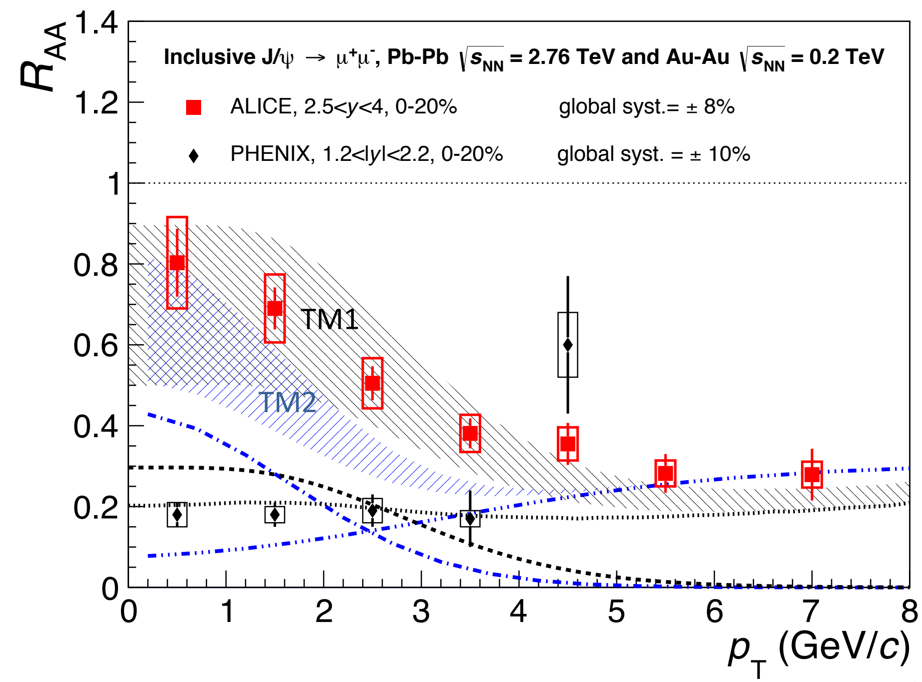
Phys. Lett. B 734, 314-327 (2014)





- Dependence on p_T opposite from what is expected from QGP dissociation
- **Models which include statistical regeneration explain the qualitative features**

Models
TM1: Zhao-Rapp NPA 859 (2011) 114
TM2 : Zhou et al., PRC 89 (2014) 054911

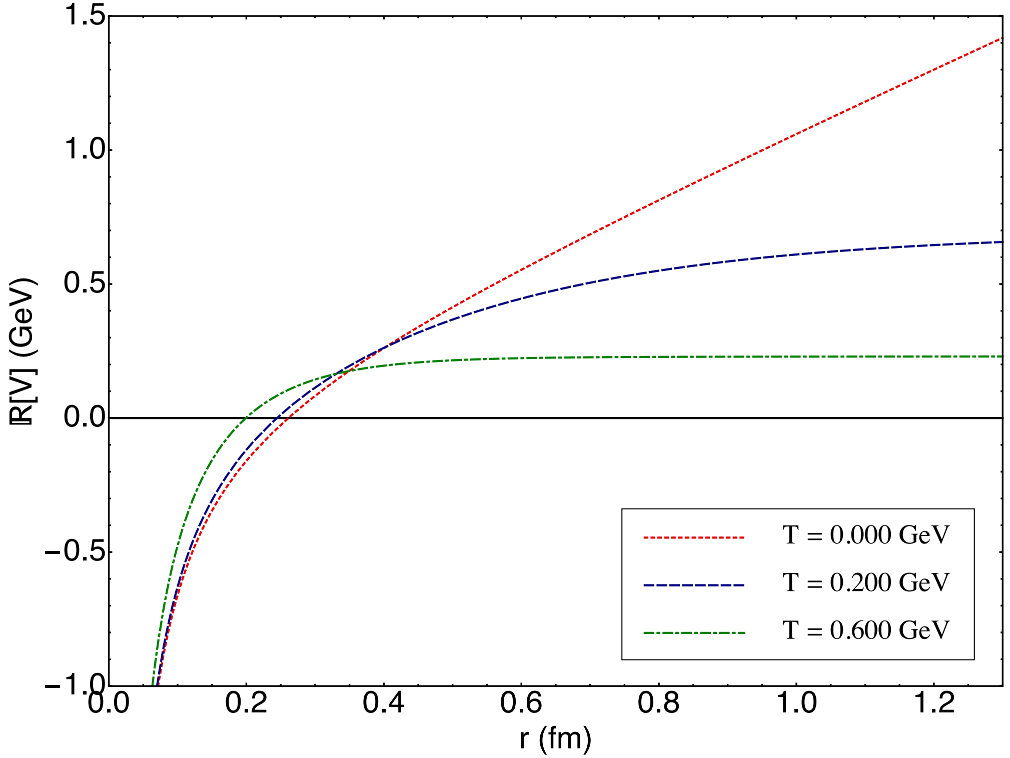


Bottomonia in AA
with some model details

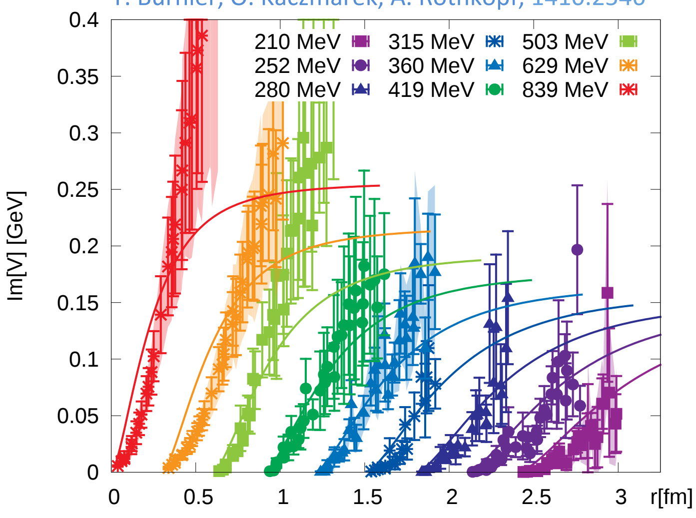
Complex-valued potential

- Potential can be parameterized as a Debye-screened potential with a direction-dependent Debye mass (anisotropy).
- Imaginary part coming from the Landau damping of the exchanged gluon!
- This imaginary part also exists in the isotropic case. Laine et al hep-ph/0611300
- Used this as a model for the free energy (F) and also obtained internal energy (U) from this.

MS, 1106.2571; Bazow and MS, 1112.2761
Dumitru, Guo, and MS, 0711.4722 and 0903.4703
Burnier, Laine, Vepsalainen, arXiv:0903.3467 (aniso)



Y. Burnier, O. Kaczmarek, A. Rothkopf, 1410.2546



Summary of the method

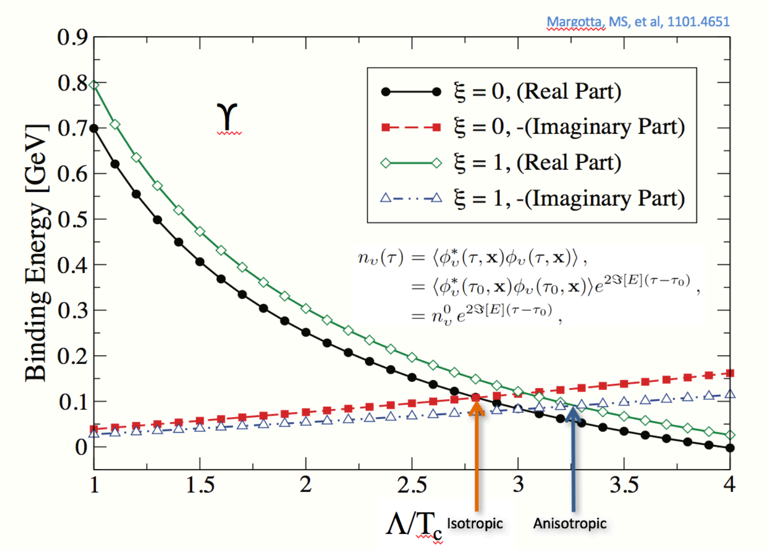
Solve the 3d Schrödinger EQ with complex-valued potential

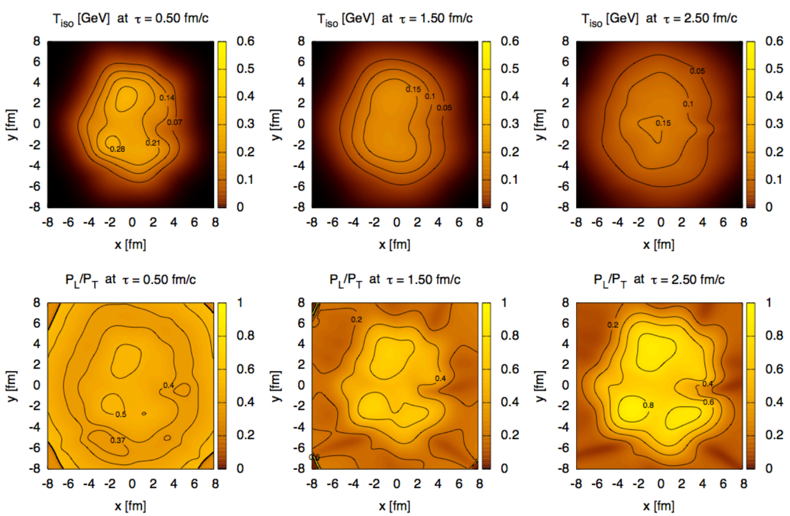
↓

Obtain real and imaginary parts of the binding energies for the Υ(1S), Υ(2S), Υ(3S), χ_b(1P), χ_b(2P), and χ_b(3P) as function of energy density and anisotropy. Yager-Elorriaga and MS, 0901.1998; Margotta, MS, et al, 1101.4651

↓

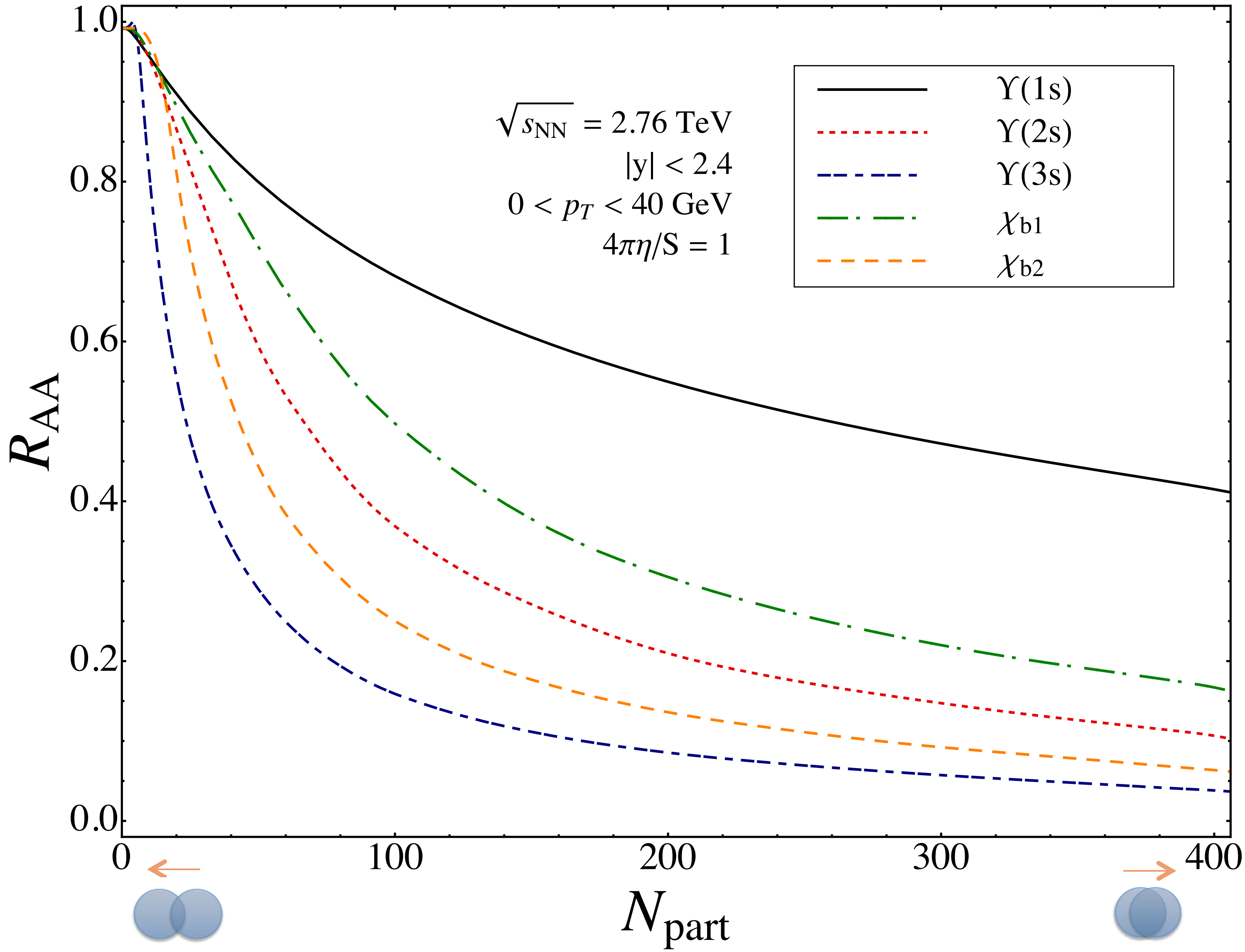
Fold together with the non-EQ spatiotemporal evolution to obtain the **survival probability**.





State Suppression Factors, $R_{AA}{}^{i}$

B. Krouppa, R. Ryblewski, and MS, Phys. Rev. C 92, 061901(R)(2015).



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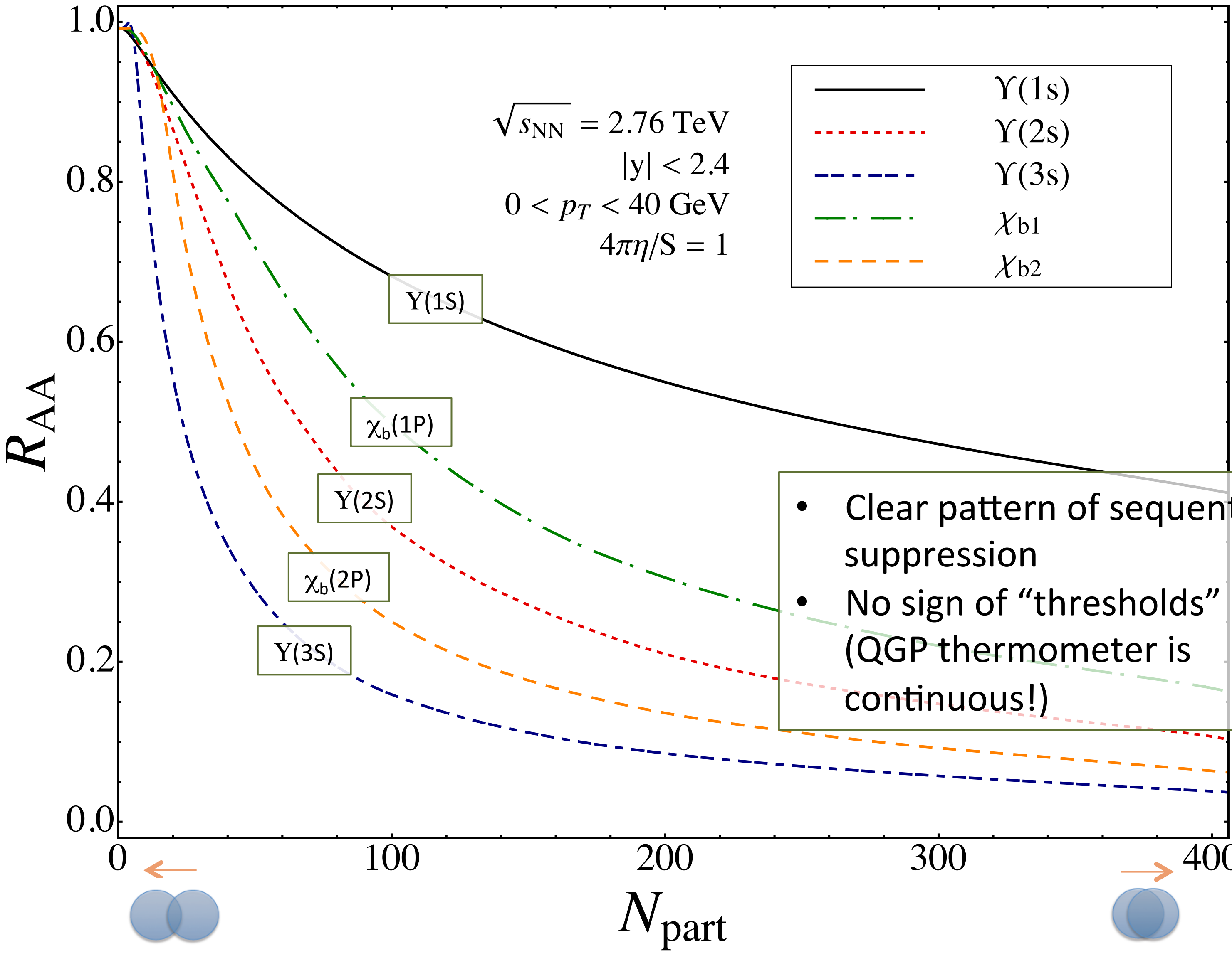
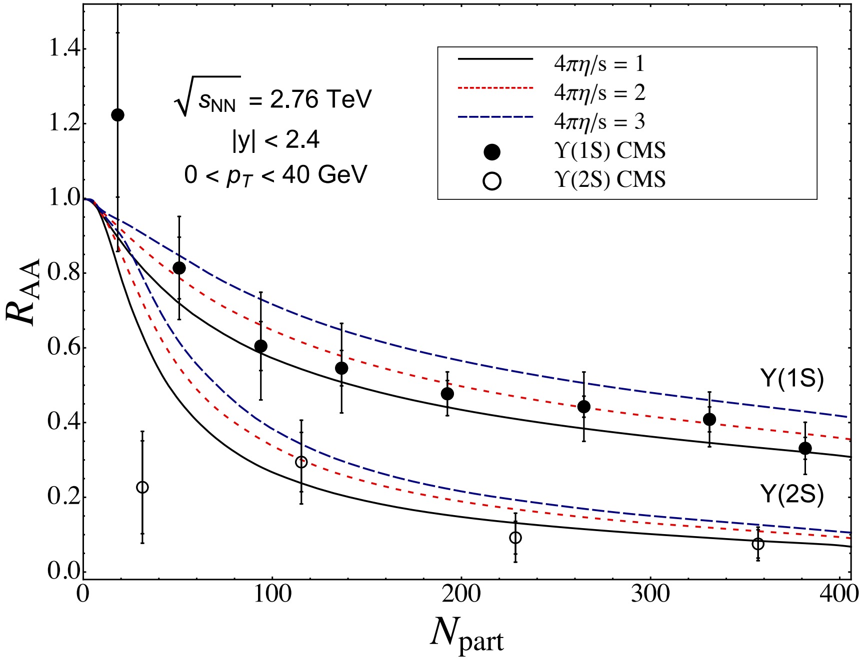


- Clear pattern of sequential suppression
- No sign of "thresholds" (QGP thermometer is continuous!)

AA collisions

arXiv:1704.02361



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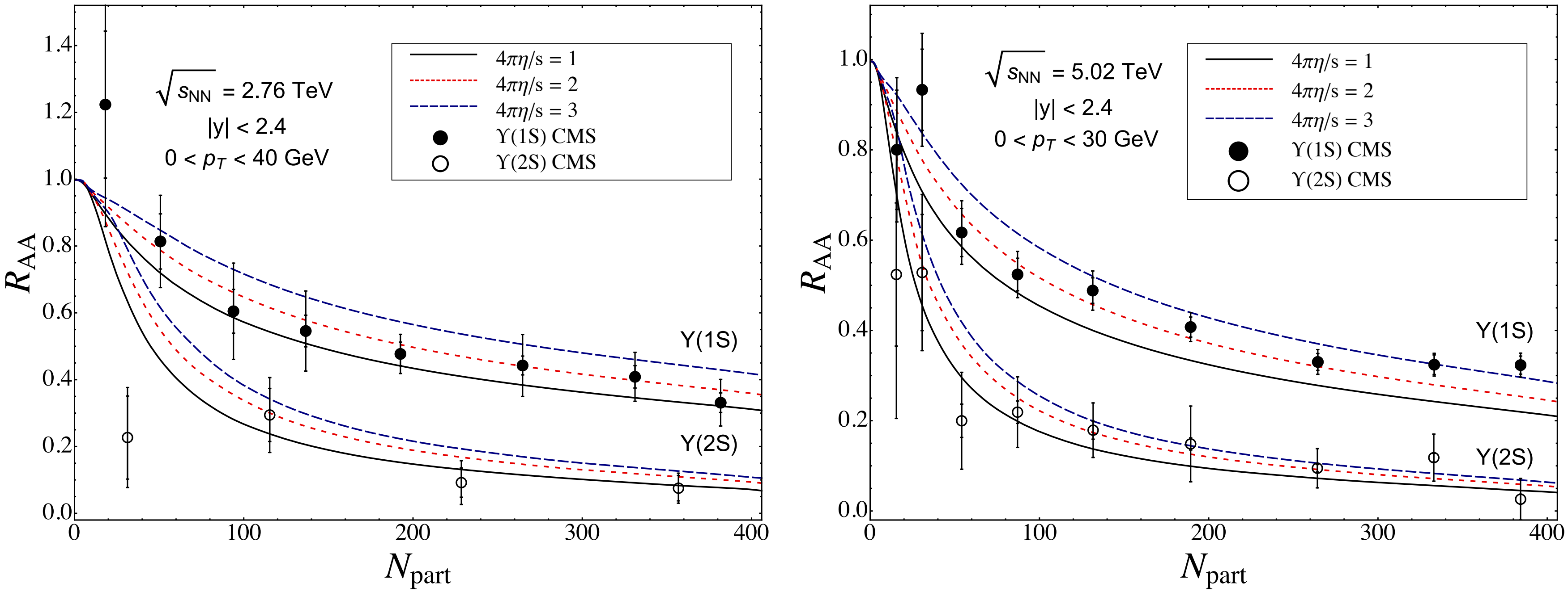

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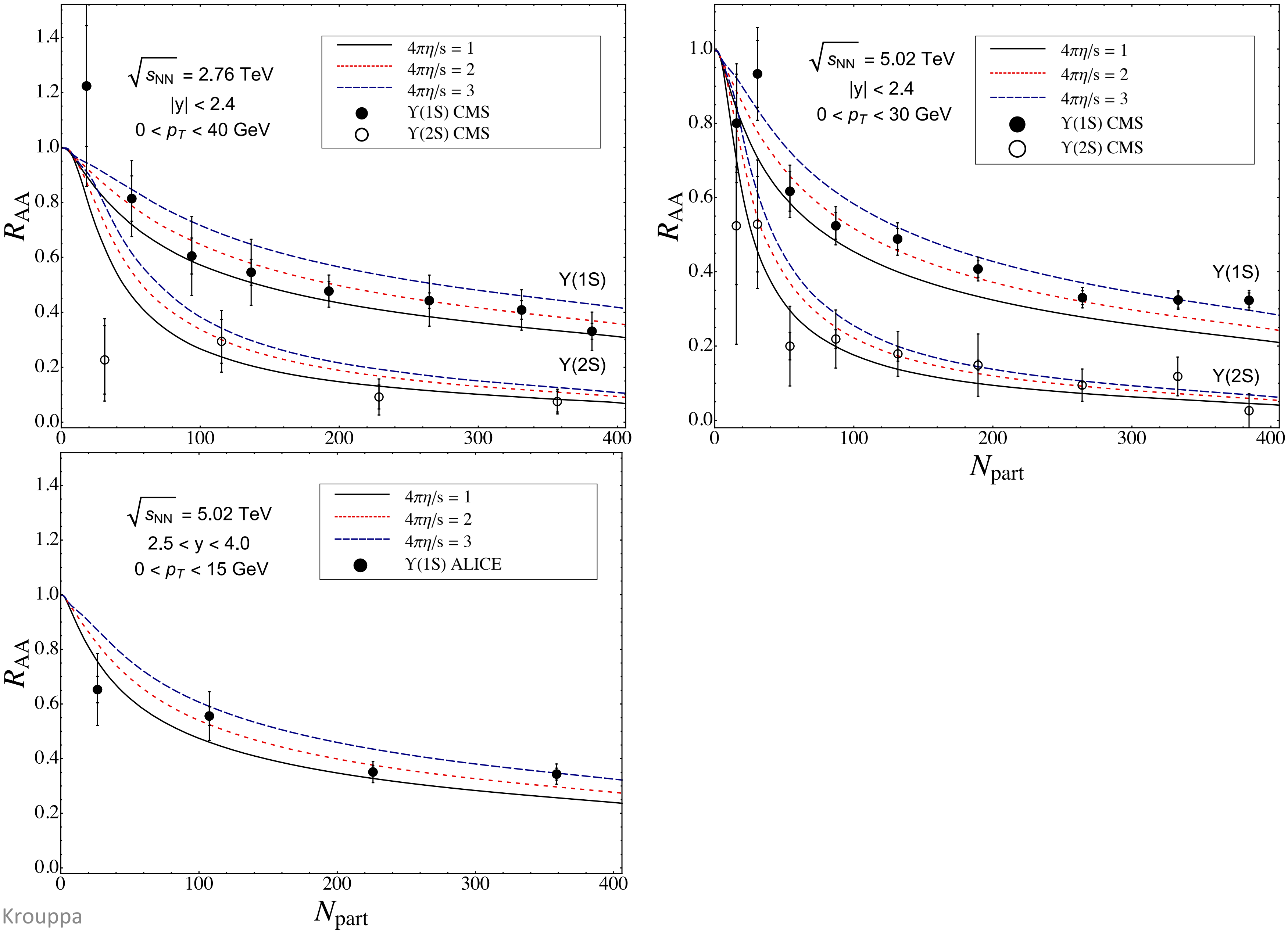

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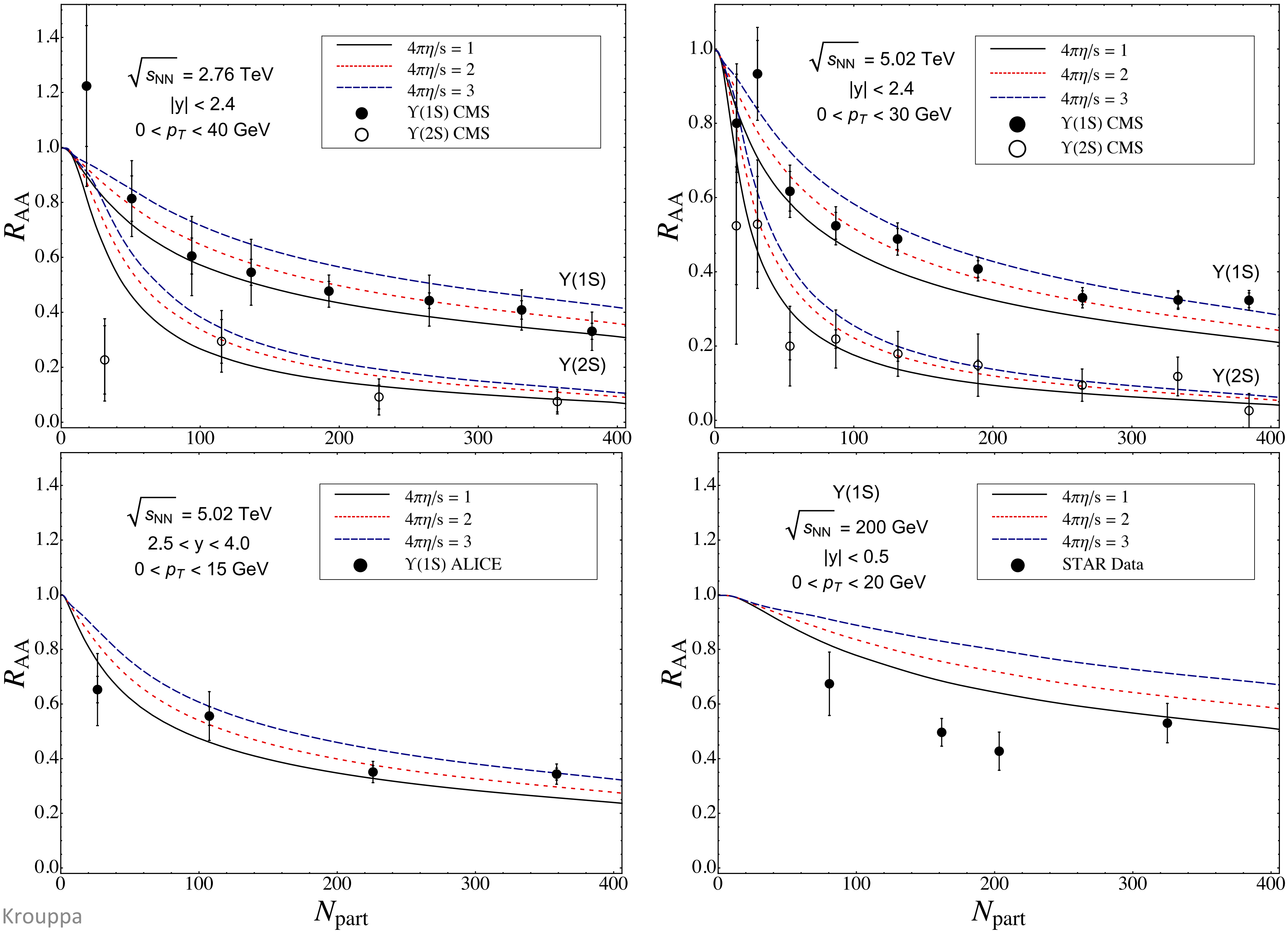

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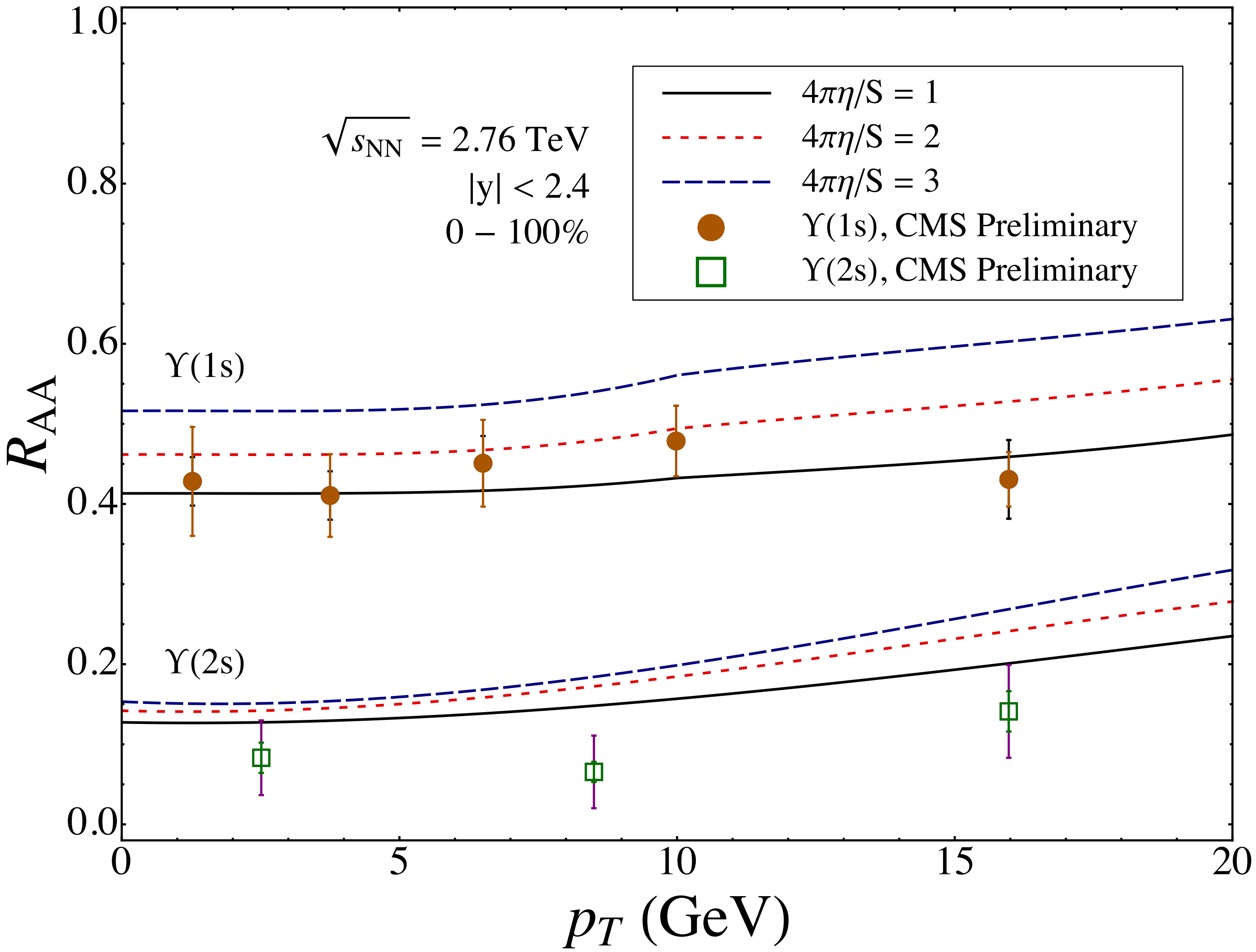

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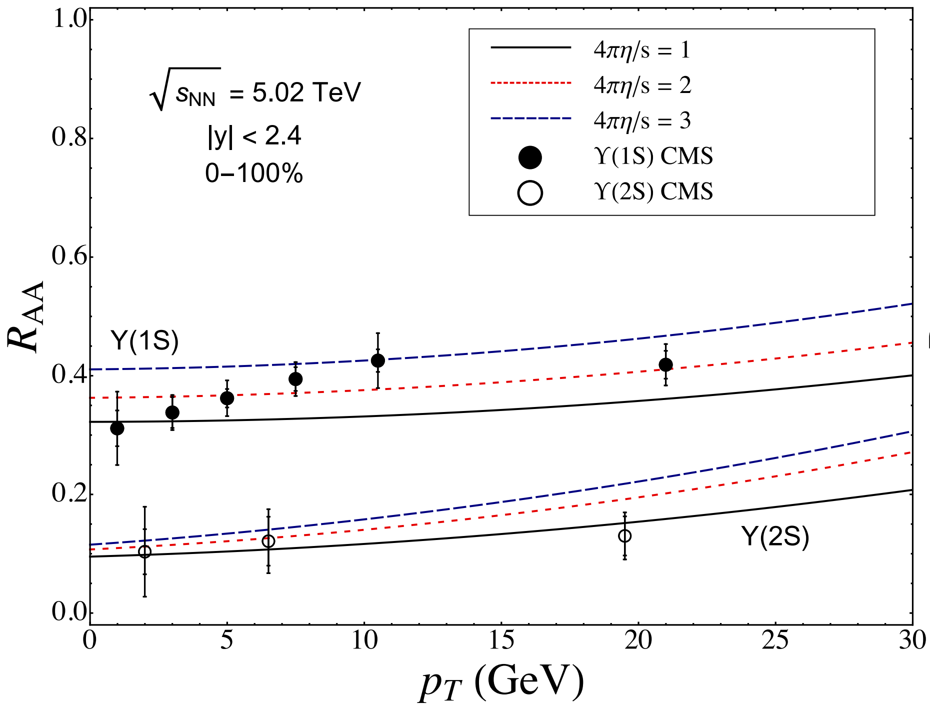

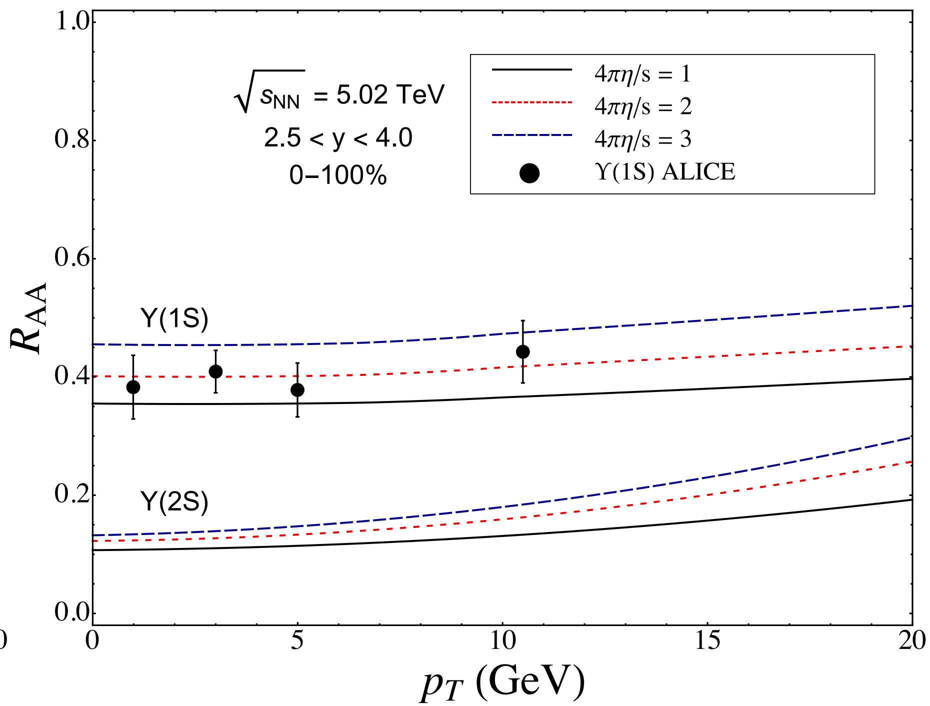

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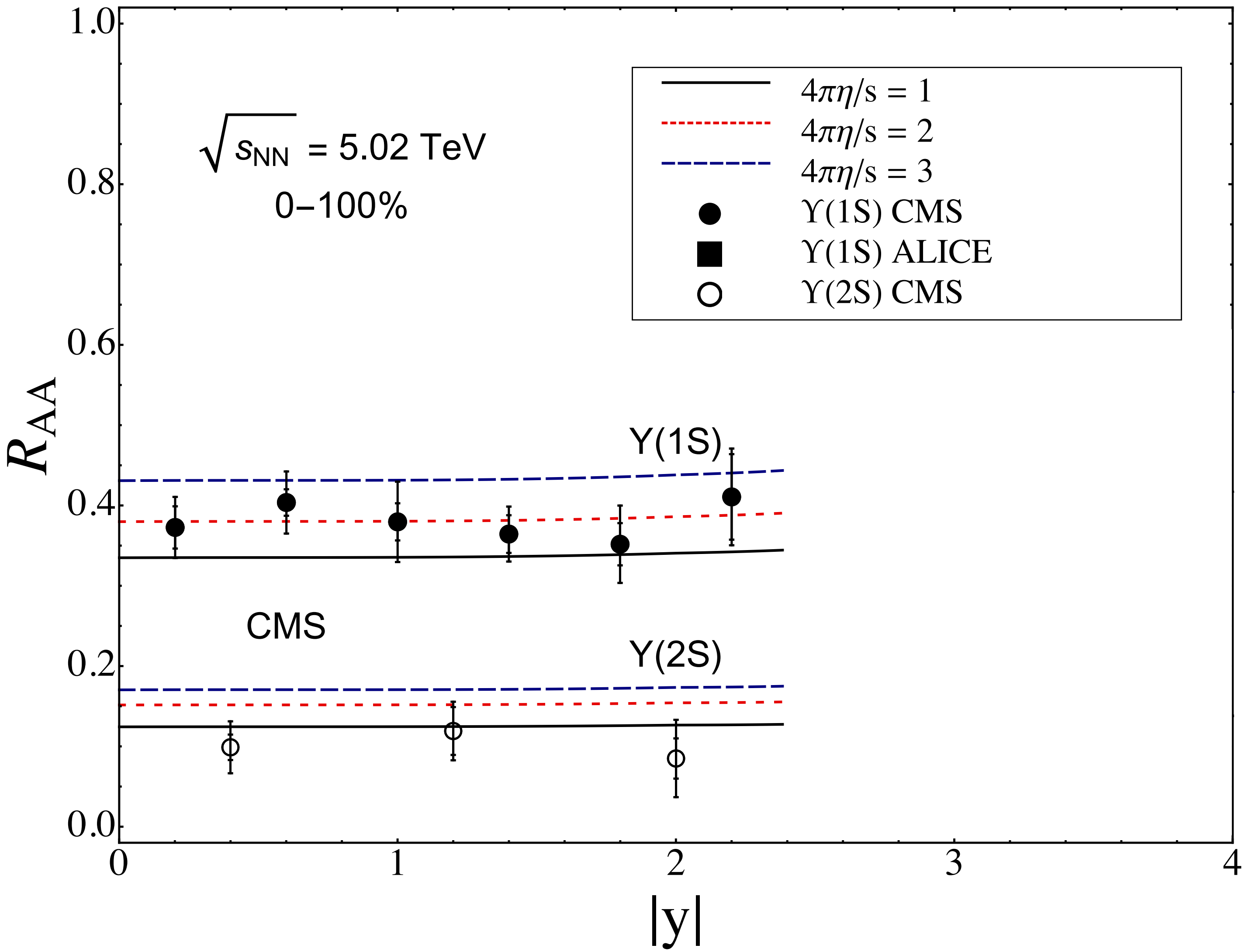

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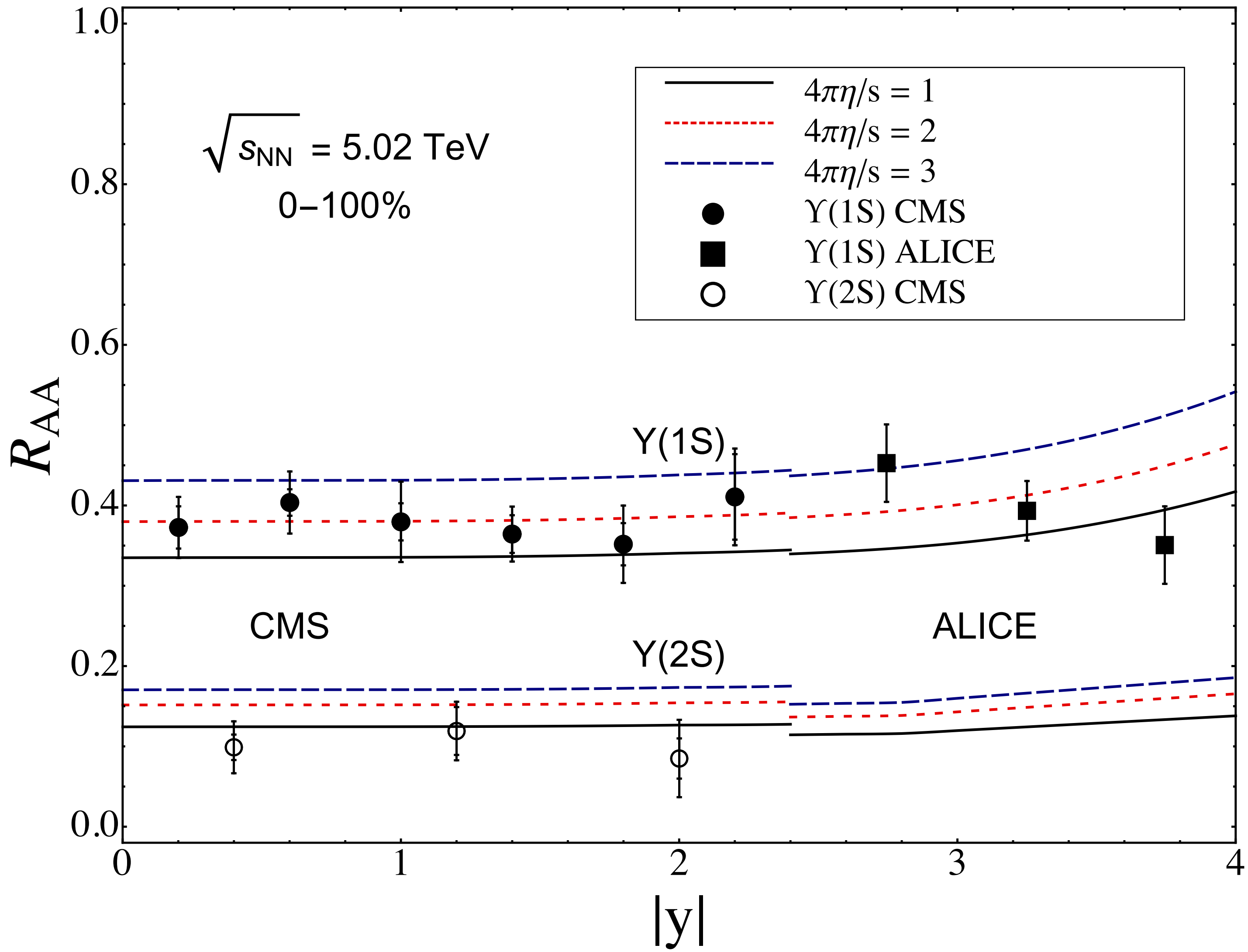
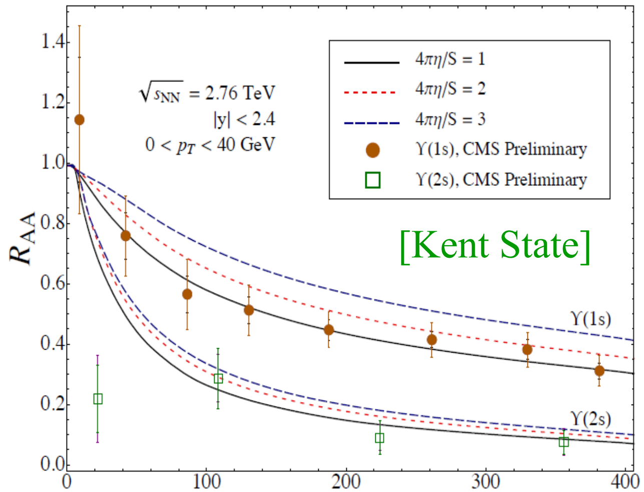
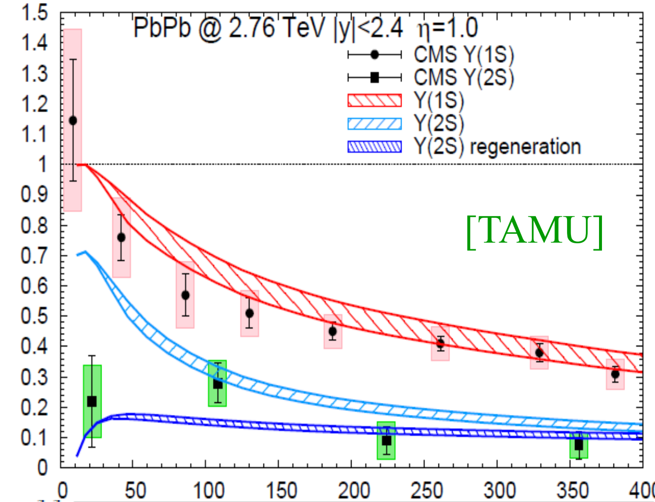


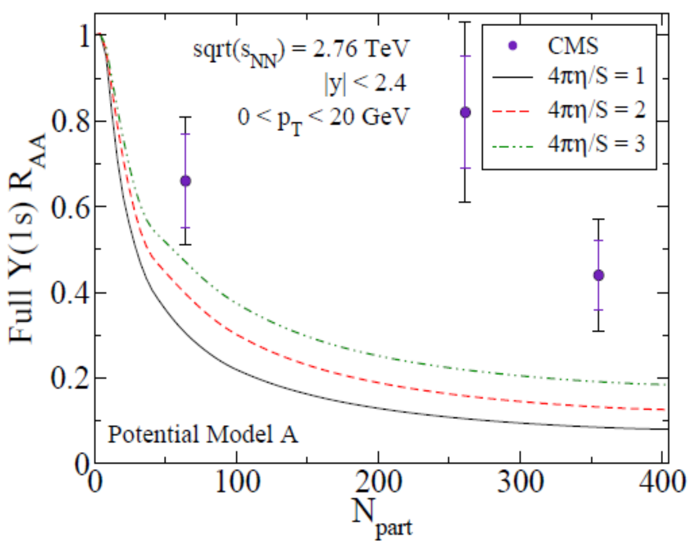
Strong or weak binding?

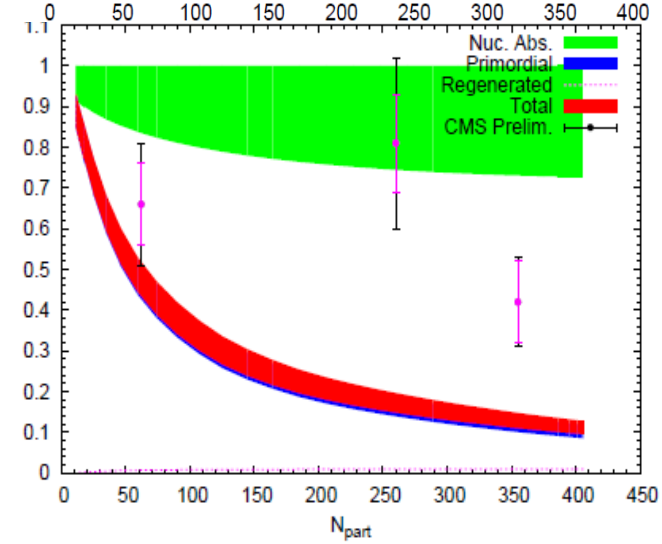
Internal "strong binding"





Free "weak binding"



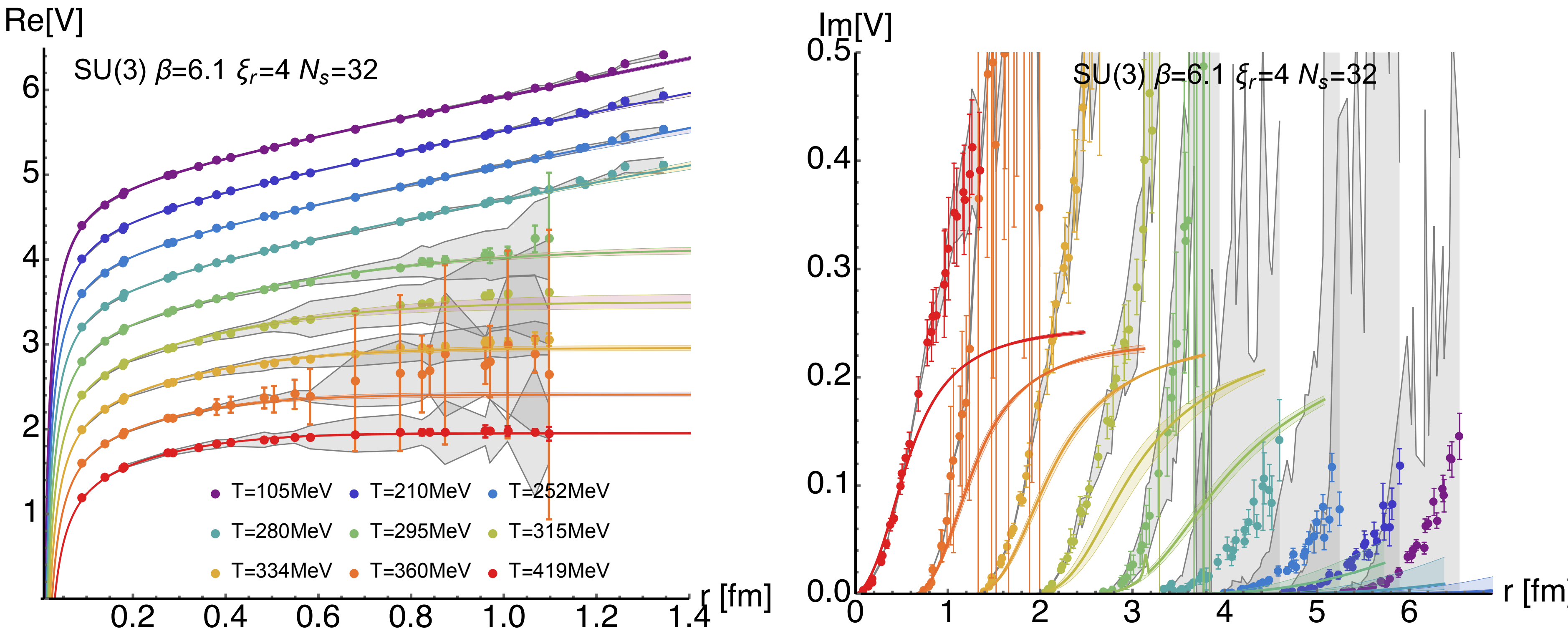


Bazow and Strickland 1112.2761,Krouppa and Strickland, 1507.03951;Rapp, QM2017

Forthcoming

Lattice-extracted potential

- Can we extract the heavy quark potential from the lattice?
- Rothkopf et al. recently published their work.
- Qualitative trends in agreement with other perturbative-inspired model.

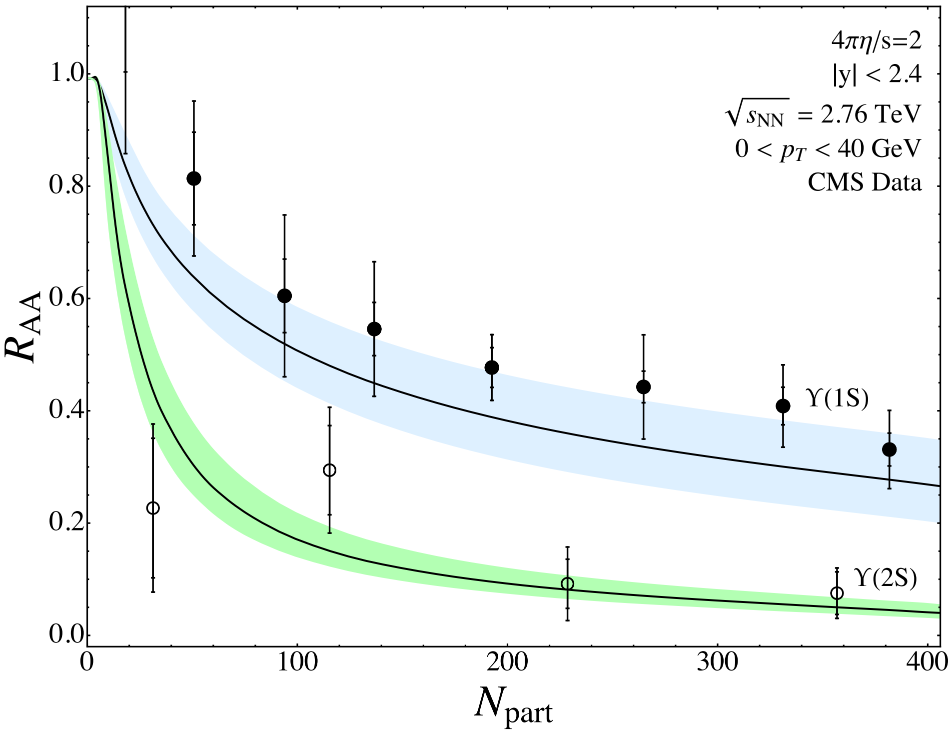


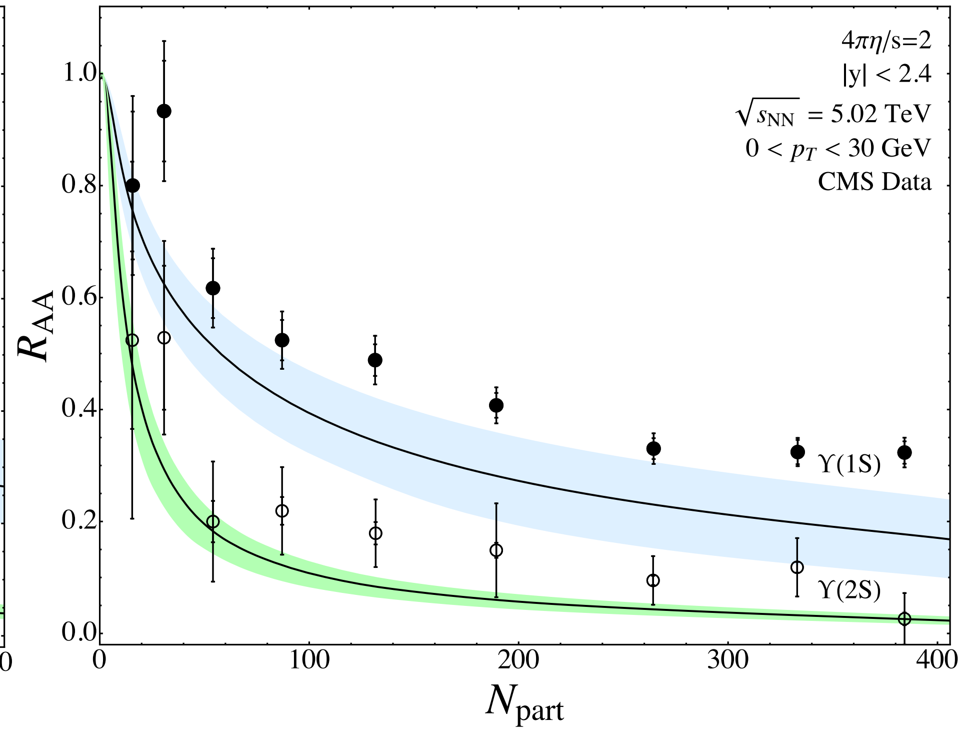
Burnier and Rothkopf, 1506.08684

Lattice-extracted potential

Forthcoming

- No eta/s dependence (not shown)
- Bands are +/-15% Debye mass variation
- More suppression seen compared to Bazow-Strickland model





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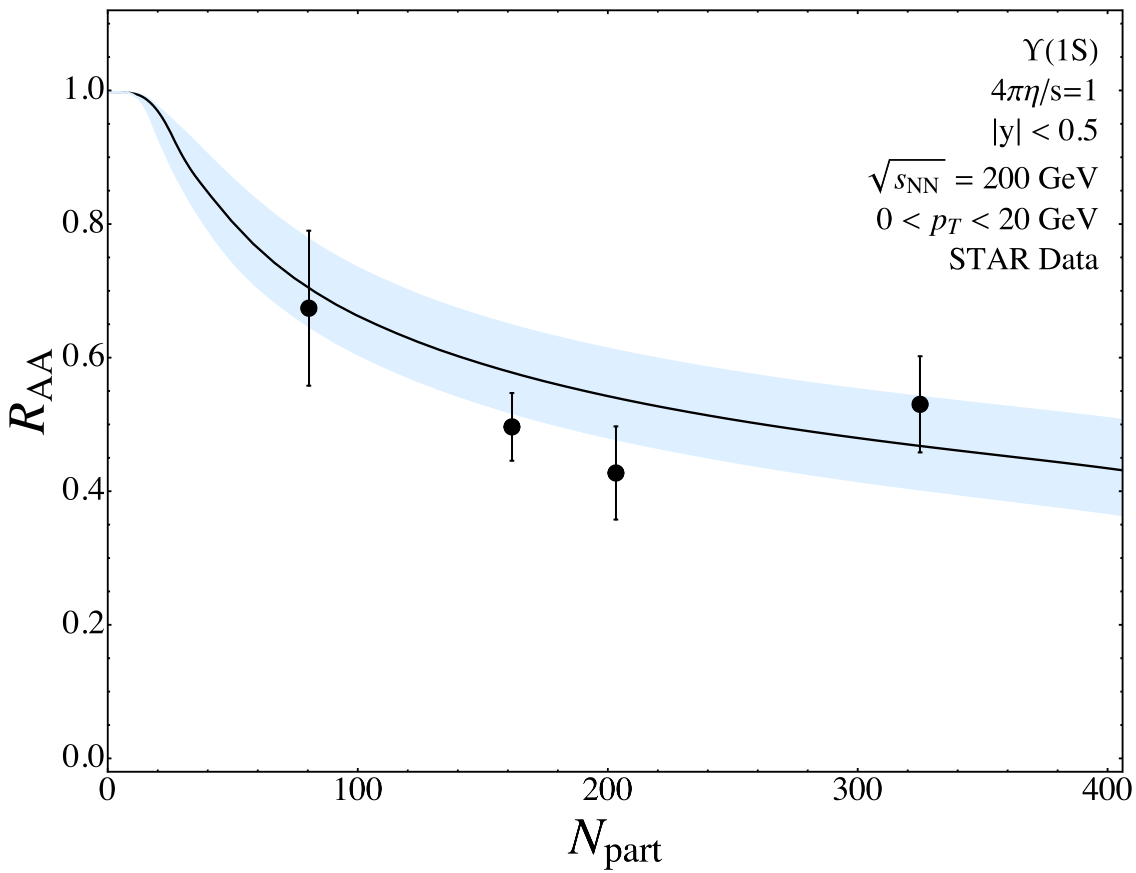

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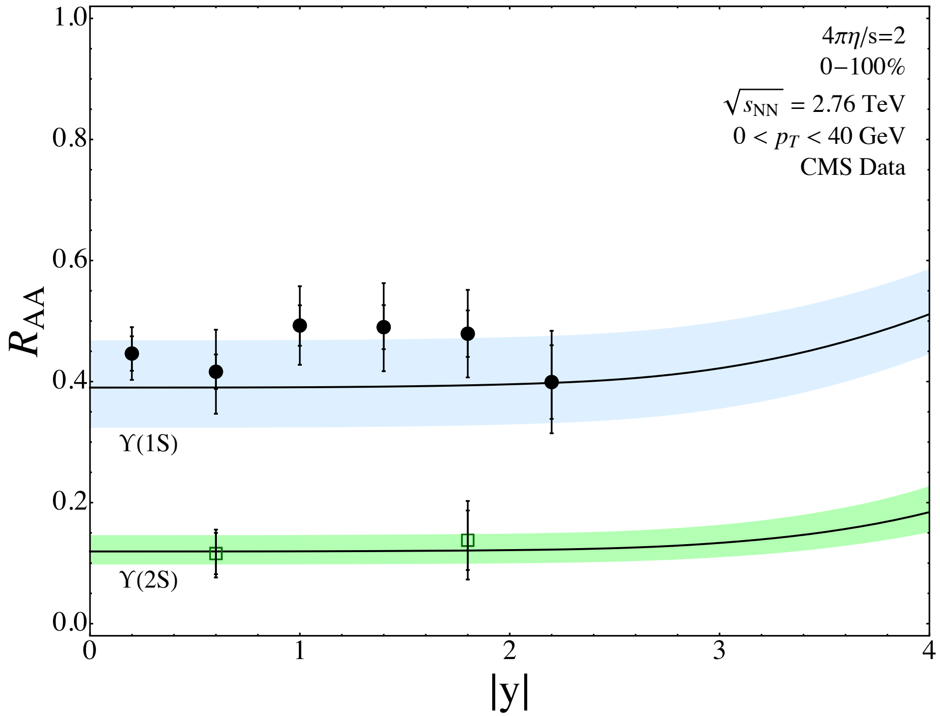
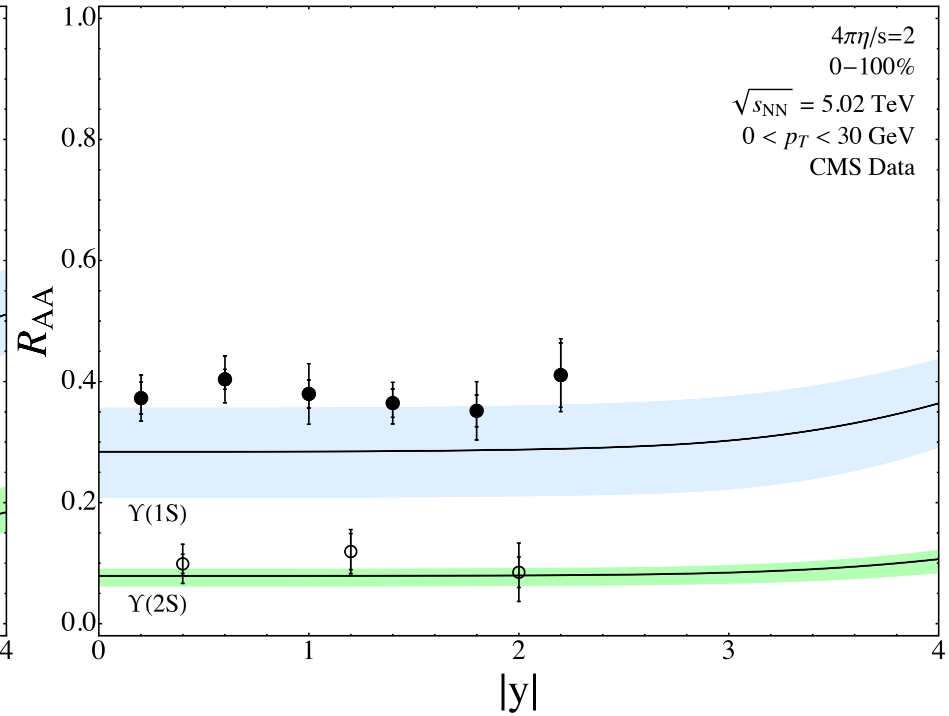
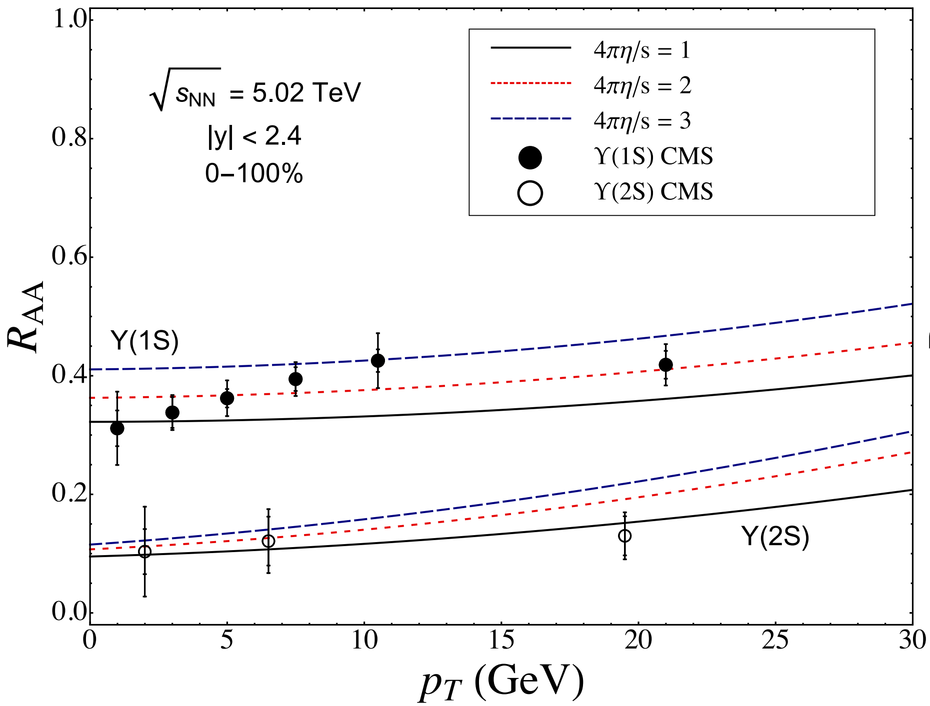
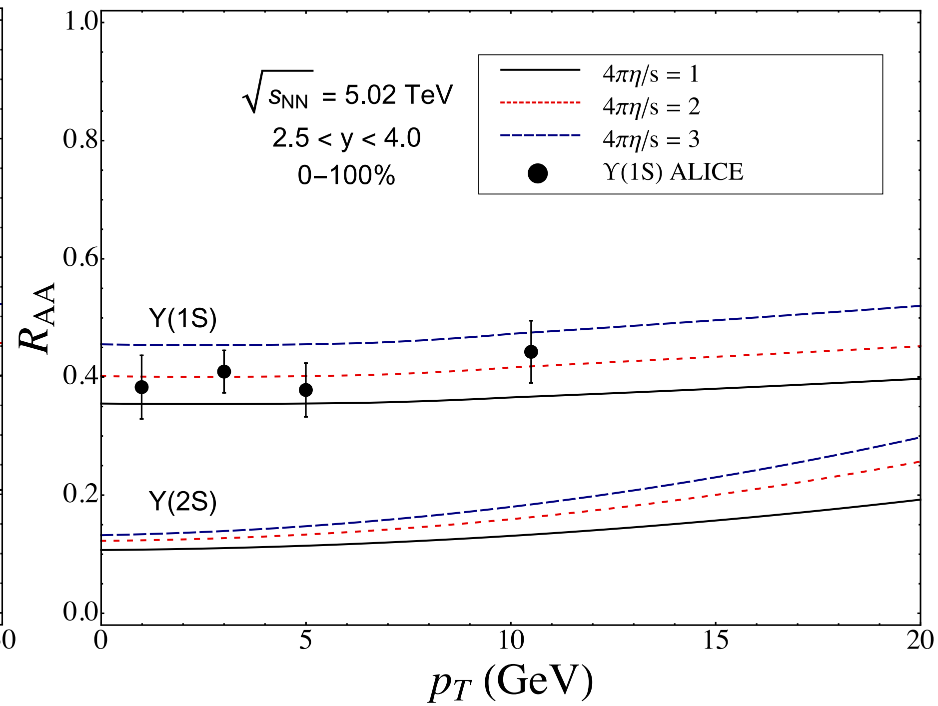




Now what???

- Case for bottomonia regeneration?
- Transverse momentum data suggests no.
- Turn to initial plasma conditions.





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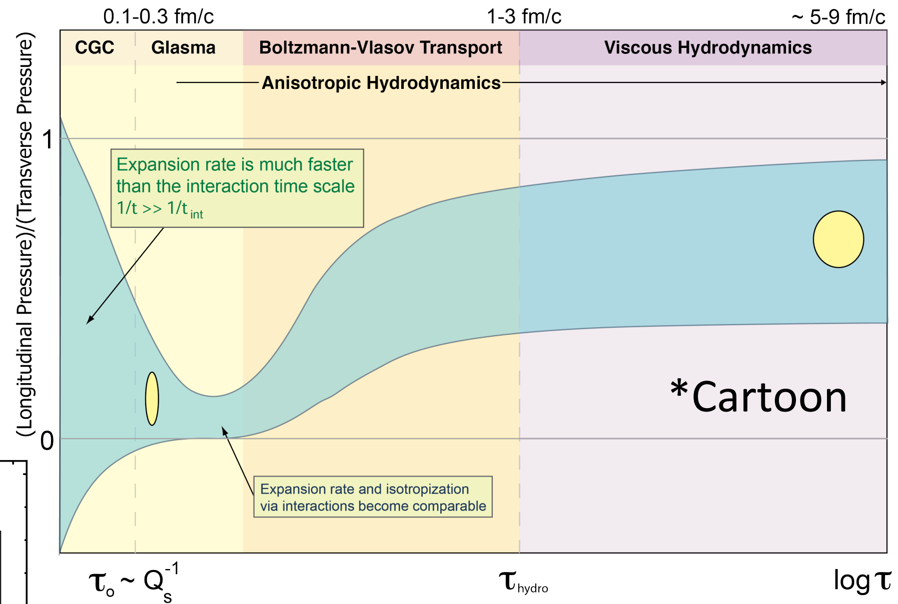
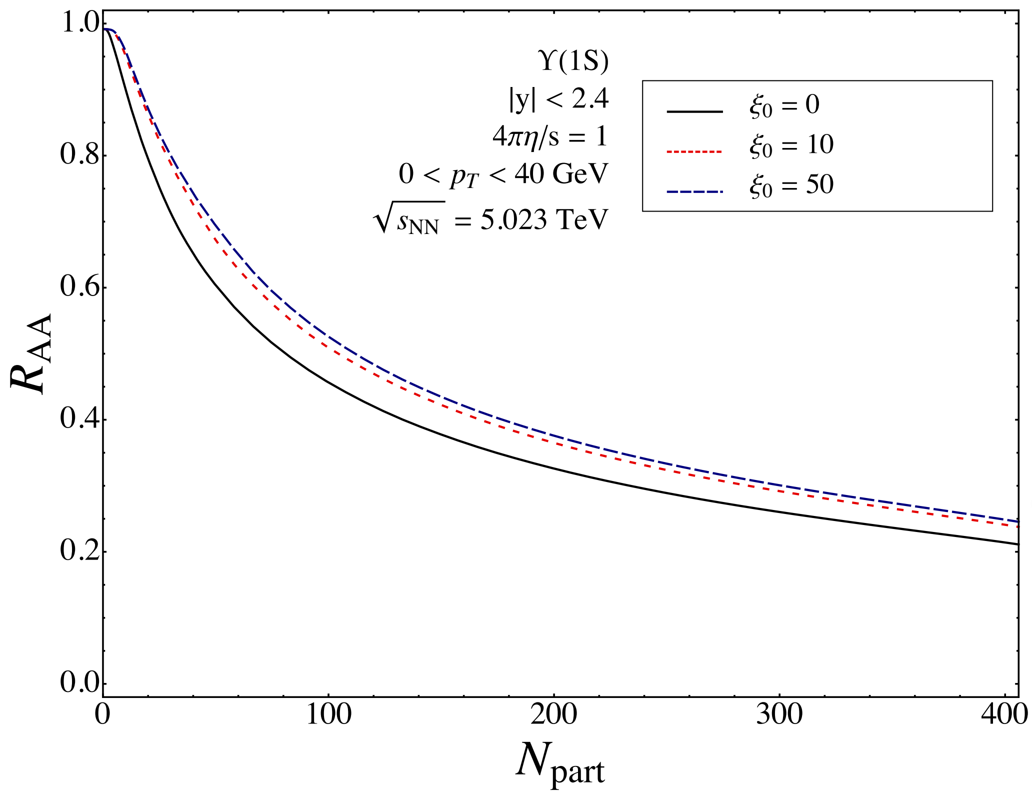
- Transverse momentum data suggests no.
- Turn to initial plasma conditions.





Finite xi reduces suppression

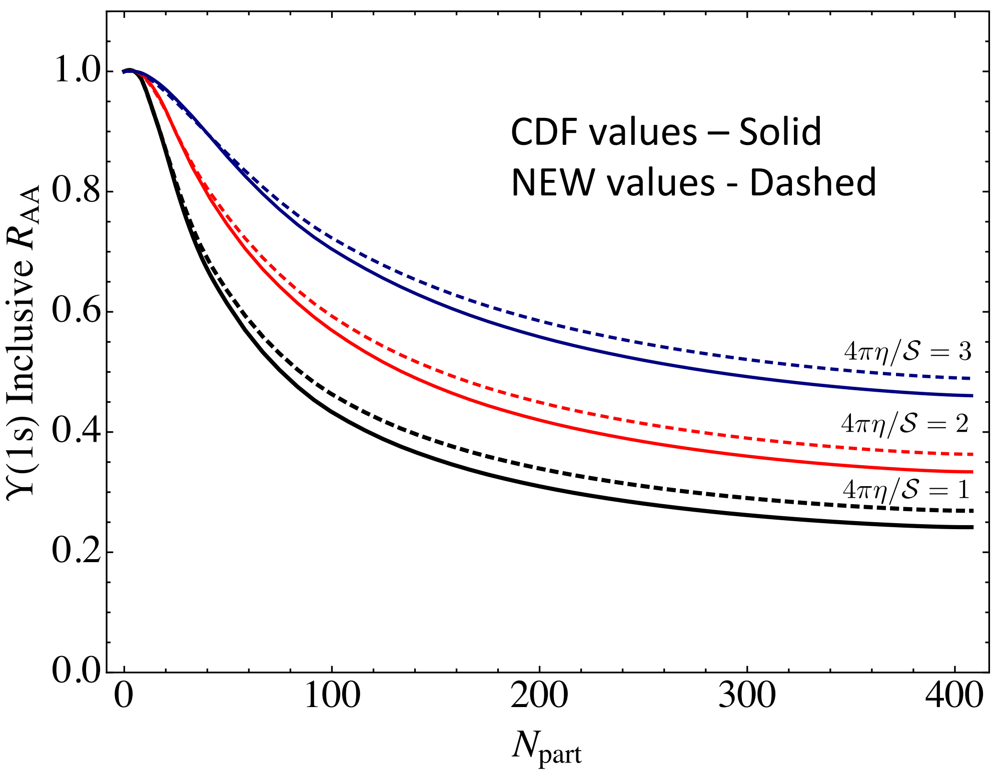
The "final" chapter

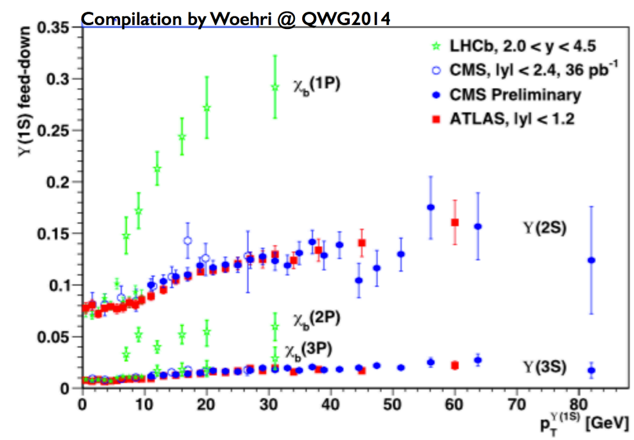
- For J/ψ, CNM effects are important.
- For J/ψ, we see signs of regeneration for $p_T < 4\text{-}5$ GeV; to see suppression directly we should apply $p_T > 5$ GeV cut.
- For Υ(1S), we might be able to get away with ignoring regeneration and/or CNM; however, going forward all effects should be included in a self-consistent manner (work in progress).
- Complex screening model works reasonably well to describe suppression seen at LHC, but some tension exists with RHIC.
- Reported early work on using lattice-extracted potential from Rothkopf et al; shows some promise, but initial results suggest too much suppression; initial xi?

Backup slides

Updated feed down fractions

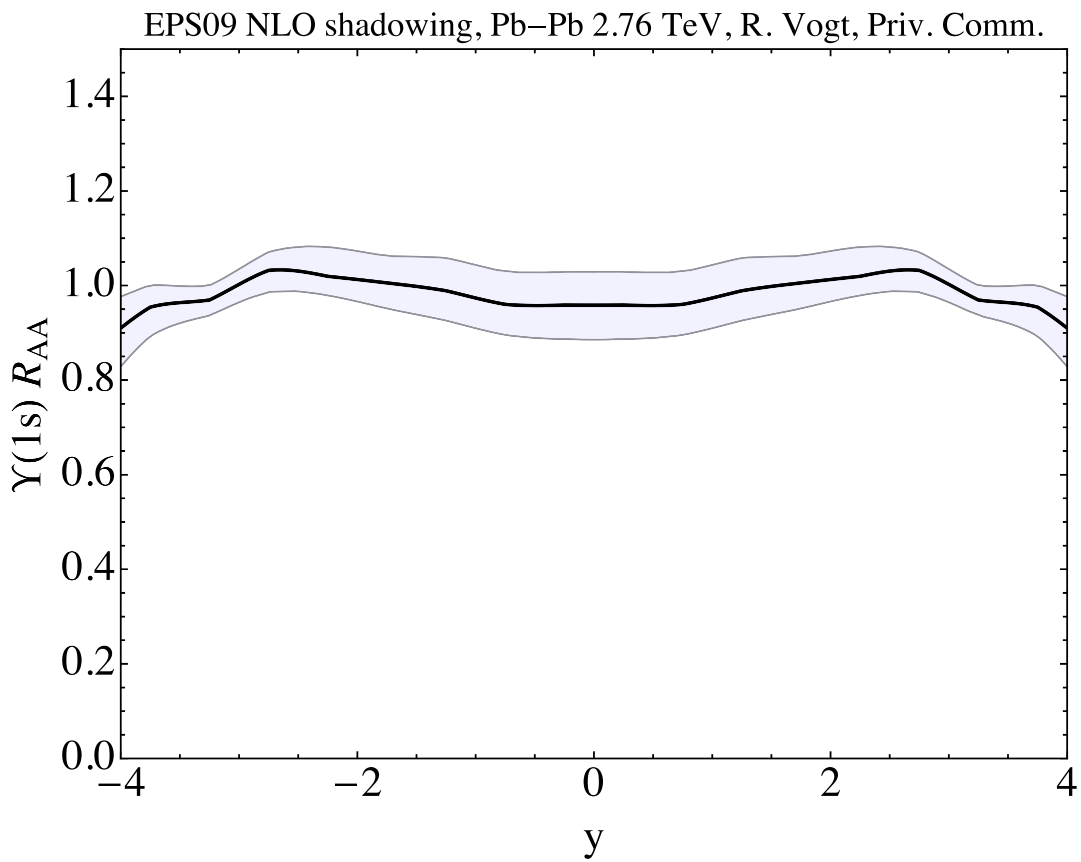
- Original feed down fractions came from CDF collaboration at Fermilab
- Better values available (p_T-dependent); we compute average p_T ~ 8.9 GeV and use the values at this point





$\Upsilon(1S)$ Feed Down Fractions	
$\Upsilon(1S)$	0.668
$\Upsilon(2S)$	0.086
$\Upsilon(3S)$	0.010
$\chi_b(1P)$	0.170
$\chi_b(2P)$	0.051
$\chi_b(3P)$	0.015

Estimate CNM effect on Bottomonium in AA



- Estimate of CNM using EPS09 NLO shadowing provided by R. Vogt
- Effect seems to be quite small
- This is good news for isolating the medium effect we are after, but doesn't help to explain the ALICE forward "anomaly"

In-medium heavy quark potential

Using the real-time formalism one can express the potential in terms of the *static* advanced, retarded, and Feynman propagators

$$\boxed{V(\mathbf{r},\xi) = -g^2 C_F \int \frac{d^3\mathbf{p}}{(2\pi)^3} \left(e^{i\mathbf{p}\cdot\mathbf{r}} - 1\right) \frac{1}{2} \left(D^{*}{}^{L}_{R} + D^{*}{}^{L}_{A} + D^{*}{}^{L}_{F} \right)}$$

Real part can be written as

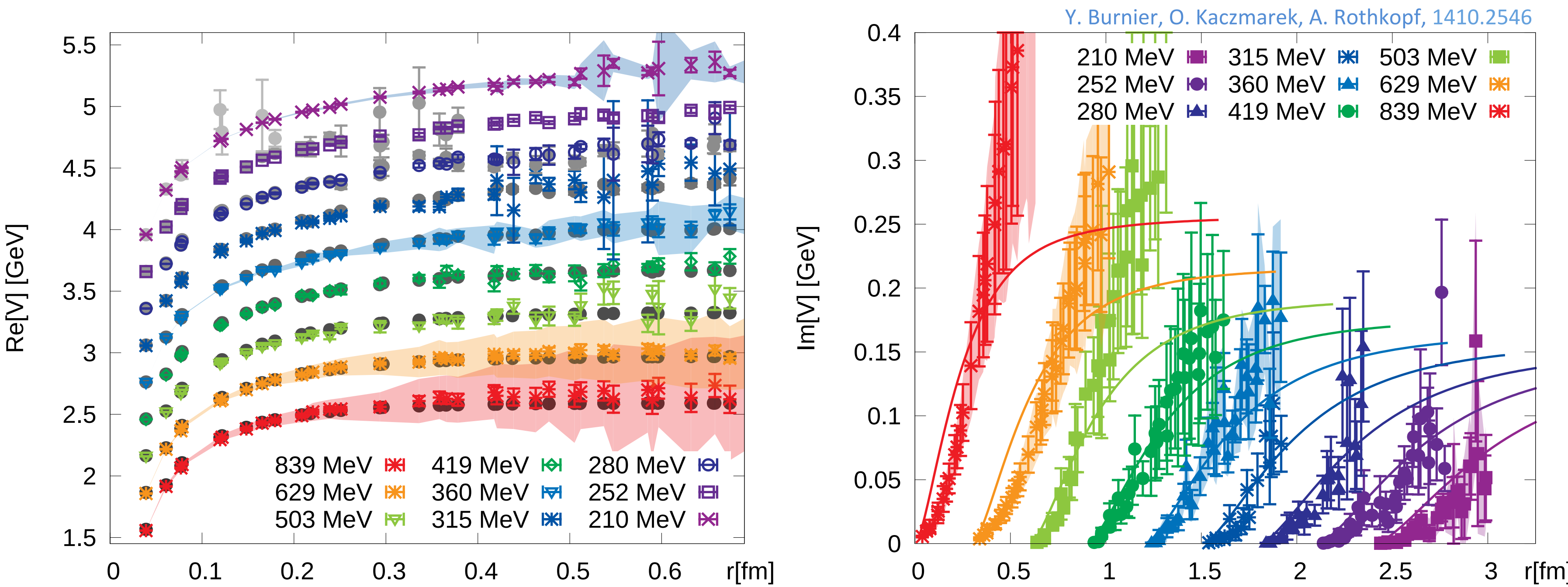
$$\mathrm{Re}[V(\mathbf{r},\xi)] = -g^2 C_F \int \frac{d^3\mathbf{p}}{(2\pi)^3} \, e^{i\mathbf{p}\cdot\mathbf{r}} \frac{\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2}{(\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2)(\mathbf{p}^2 + m_\beta^2) - m_\delta^4}$$

With <u>direction-dependent masses</u>, e.g.

$$m_\alpha^2 = -\frac{m_D^2}{2p_\perp^2\sqrt{\xi}} \left(p_z^2 \arctan\sqrt{\xi} - \frac{p_z \mathbf{p}^2}{\sqrt{\mathbf{p}^2 + \xi p_\perp^2}} \arctan \frac{\sqrt{\xi} p_z}{\sqrt{\mathbf{p}^2 + \xi p_\perp^2}} \right)$$

Anisotropic potential calculation: Dumitru, Guo, and MS, 0711.4722 and 0903.4703
Gluon propagator in an anisotropic plasma: Romatschke and MS, hep-ph/0304092

Sanity check



- Results above are the real and imaginary part of the heavy quark potential extracted from the lattice.
- For the imaginary part, the authors also compare with the isotropic Im[V] indicated on the previous slide.

The suppression factor

- Resulting decay rate Γ = -2 Im[E_{bind}] is a function of τ, $x_\perp$, and ς (spatial rapidity). First we need to integrate over proper time

$$\bar{\gamma}(\mathbf{x}_\perp, p_T, \varsigma, b) \equiv \int_{\max(\tau_{\rm form}(p_T),\tau_0)}^{\tau_f} d\tau\, \Gamma_T(\tau, \mathbf{x}_\perp, \varsigma, b)$$

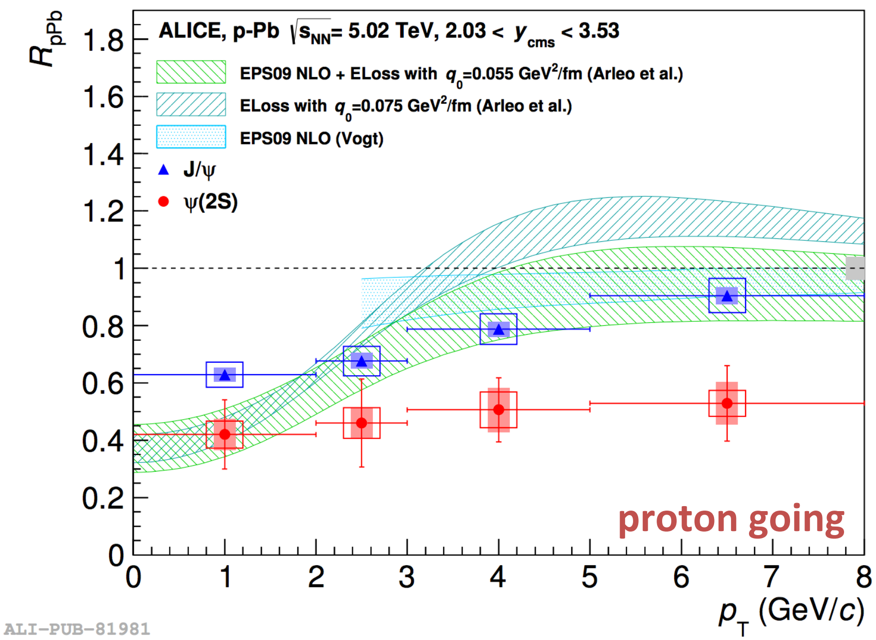
- From this we can extract R_{AA}

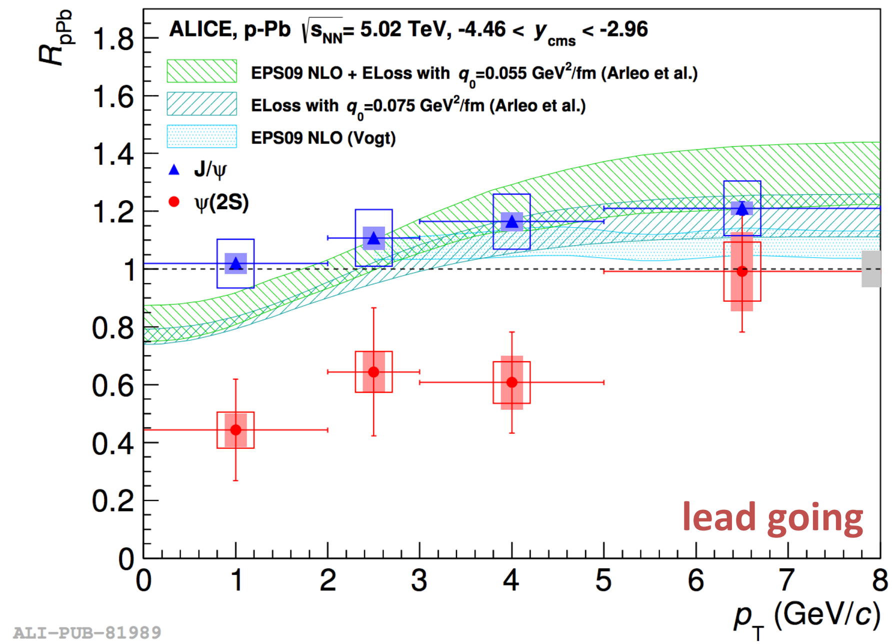
$$R_{AA}(\mathbf{x}_\perp, p_T, \varsigma, b) = \exp(-\bar{\gamma}(\mathbf{x}_\perp, p_T, \varsigma, b))$$

- Use the overlap density as the probability distribution function for quarkonium production vertices and geometrically average

$$\langle R_{AA}(p_T, \varsigma, b)\rangle \equiv \frac{\int_{\mathbf{x}_\perp} d\mathbf{x}_\perp\, T_{AA}(\mathbf{x}_\perp)\, R_{AA}(\mathbf{x}_\perp, p_T, \varsigma, b)}{\int_{\mathbf{x}_\perp} d\mathbf{x}_\perp\, T_{AA}(\mathbf{x}_\perp)}$$

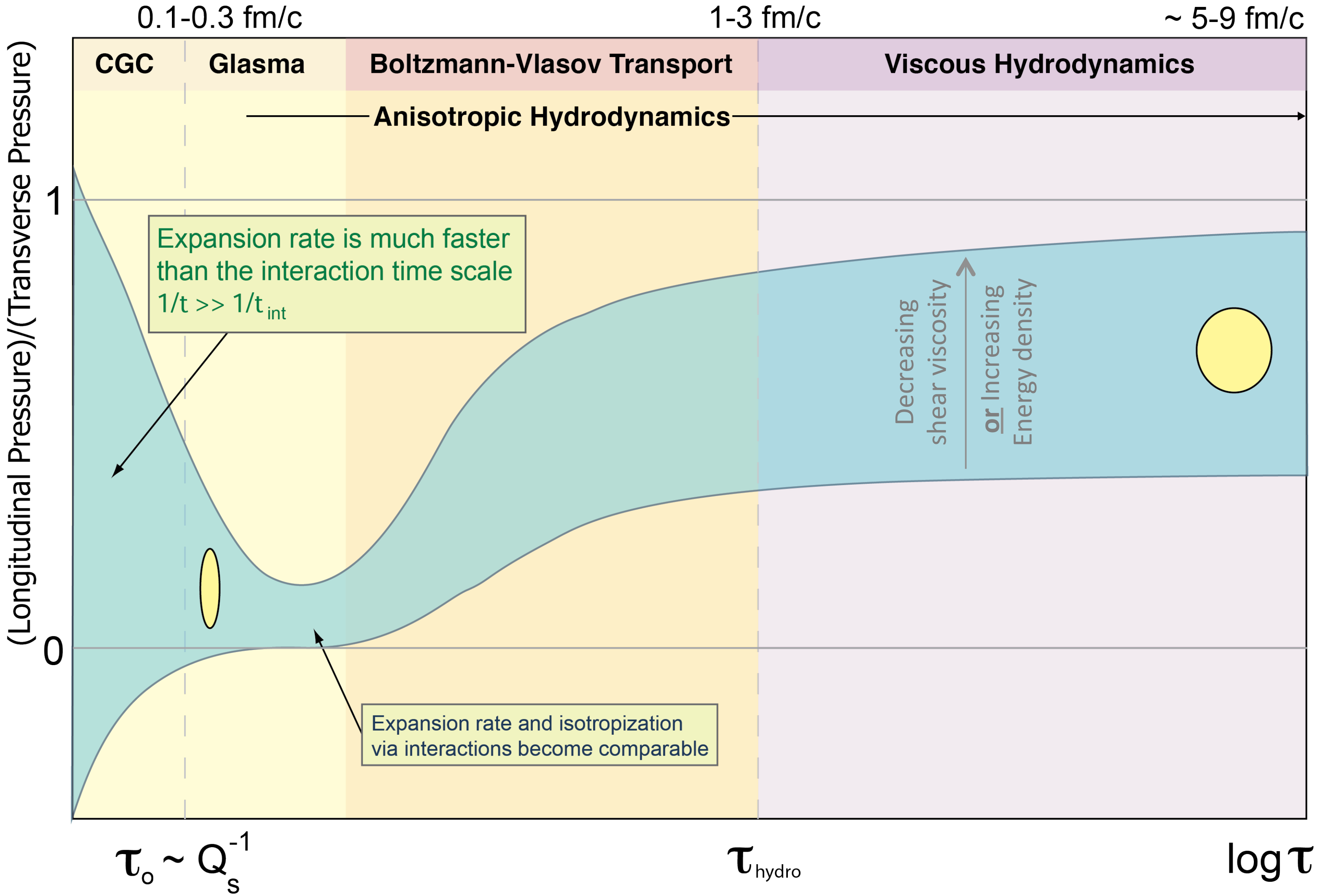
pA - Charmonia states





- Backward and forward rapidity: larger ψ(2s) suppression relative to the J/ψ
- R_{pPb} increases with p_T
- In most models shadowing and energy loss are expected to be almost identical; cannot describe the large ψ(2s) suppression; need enhanced **suppression from co-movers**?

QGP momentum anisotropy cartoon



B. Krouppa

Anisotropic hydrodynamics basics

[M. Martinez and MS, 1007.0889]
[W. Florkowski and R. Ryblewski, 1007.0130]

Viscous Hydrodynamics Expansion

$$f(\tau, \mathbf{x}, \mathbf{p}) = \underbrace{f_{\text{eq}}(\mathbf{p}, T(\tau, \mathbf{x}))}_{\text{Isotropic in momentum space}} + \delta f$$

Non-equilibrium corrections from e.g. shear stress

Anisotropic Hydrodynamics (aHydro) Expansion

$$f(\tau, \mathbf{x}, \mathbf{p}) = f_{\text{aniso}}(\mathbf{p}, \underbrace{\Lambda(\tau, \mathbf{x})}_{T_\perp}, \underbrace{\xi(\tau, \mathbf{x})}_{\text{anisotropy}}\ ) + \delta\tilde{f}$$

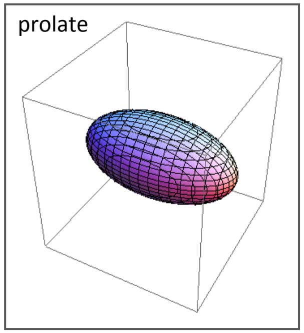
Treat this term perturbatively
→ "NLO aHydro"

D. Bazow, U. Heinz, and MS, 1311.6720
D. Bazow, U. Heinz, and M. Martinez, 1503.07443

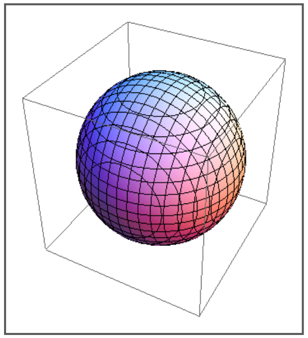
→ "Romatschke-Strickland" form in LRF

$$\boxed{f_{\text{aniso}}^{LRF} = f_{\text{iso}}\left(\frac{\sqrt{\mathbf{p}^2 + \xi(\mathbf{x}, \tau) p_z^2}}{\Lambda(\mathbf{x}, \tau)}\right)}$$

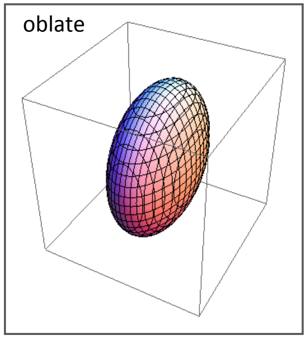
$$\boxed{\xi = \frac{\langle p_T^2 \rangle}{2\langle p_L^2 \rangle} - 1}$$



$-1 < \xi < 0$



$\xi = 0$



$\xi > 0$

Good news and bad news

- Large binding energies → short formation times
- Formation time for Υ(1S), for example, is ≈ 0.2 fm/c
- This comes at a cost: **We need to reliably model the early-time dynamics since quarkonia are born into it.**
- In addition, production vertices can be anywhere in the transverse plane, not just the central hottest region.
- For example, for a central collision <r> ~ 3.2 fm and the most probable r is ~ 5 fm.
- **We need to reliably describe the dynamics in the full 3+1d volume.**